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LASER WELDING

by R. J. SCHWINGHAMER
Manufacturing Engineering Laboratory

NASA

George C. Marshall
Space Flight Center,
Huntsville, Alabama

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TECHNICAL MEMORANDUM X- 53285

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ABSTRACT

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A comprehensive analysis of the current state of the art in high powered lasers and laser welding is presented. Among the pertinent subjects discussed are basic laser types and the MSFC 240 kilojoule system including the gun, focussing system, power supply, pulse forming network and diagnostics. Welding aspects are considered in detail and "Q" spoiling techniques, pulse repetition rate and pulse width effects are explored. The future of continuous wave lasers for welding is discussed, and pertinent general laser information is given in the appendix.

author

NASA - GEORGE C. MARSHALL SPACE FLIGHT CENTER

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LASER WELDING

By

R. J. Schwinghamer

MANUFACTURING ENGINEERING LABORATORY
RESEARCH AND DEVELOPMENT OPERATIONS

ACKNOWLEDGEMENT

The author regrets the impracticality of giving credit to all whose work merits it, but would like in particular to acknowledge the contributions of J. R. Rasquin, L. E. Foster, C. R. Cooper, K. C. Smith, M. J. Whittington, and our graduate, co-op, and summer students on this project.

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DEFINITION OF TERMS AND SYMBOLS

Ångstrom; angstrom unit; Å	Ångstrom unit is employed for expressing wavelengths of light, ultra-violet radiations and X-rays. It equals 10^{-8} cm.
cm^{-1}	Wave number frequently used in laser literature instead of wavelength (λ). It is simply wavelengths per centimeter
μ	10^{-3} mm (micron)
h	Planck's constant (6.547×10^{-27} erg-sec)

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TECHNICAL MEMORANDUM X-53285

LASER WELDING

SUMMARY

A comprehensive analysis of the current state of the art in high powered lasers and laser welding is presented. Among the pertinent subjects discussed are basic laser types and the MSFC 240 kilojoule system including the gun, focussing system, power supply, pulse forming network and diagnostics. Welding aspects are considered in detail and "Q" spoiling techniques, pulse repetition rate and pulse width effects are explored. The future of continuous wave lasers for welding is discussed, and pertinent general laser information is given in the appendix.

SECTION I. INTRODUCTION

So far, the laser has evolved neither as a welding panacea, as claimed in many of the more spectacular early newspaper accounts, nor is it the epitome of uselessness, as contended by some of its more vociferous detractors. As frequently the case in complex technological developments, a process of gradual improvement is the general rule, rather than progress by any sustained "quantum jump" type advancement. This has also been true for the laser. Laser technology may have progressed to the verge of one of these quantum jumps recently as a result of a new gas laser development. In this memorandum conventional laser systems are discussed first, followed by a discussion of gas laser developments.

SECTION II. TYPES OF LASERS

A. GENERAL

There are six basic types of lasers:

1. Doped-crystal
2. Gas discharge
3. Semiconductor junction
4. Liquid
5. Plastic
6. Glass

The wavelengths produced by lasers currently range between 4880 Angstroms

($\approx$ 20.493 cm^{-1}) and 12.9 microns ($\approx$ 775 cm^{-1}) for an argon laser. A list of operating wavelengths can be seen in Appendix A.

It should be pointed out that the list of materials which exhibit lasing properties is growing rapidly and any attempt to publish a compreshensive list is doomed to failure, since new leasing combinations are being reported almost daily.

Until recently, the doped crystal lasers were thought to have the greatest potential for welding applications. The crystals are probably still the most powerful lasers at the present time. Two particular crystals, trivalent neodymium (Nd^{+++}) in barium crown glass base, and trivalent chromium in aluminum oxide (Cr^{+++} in Al_2O_3) commonly referred to as ruby,. have appeared particularly promising, and consequently, have received much attention where high power is required [1]. Since these two materials are so widely used, some specific consideration of their applicability is probably in order. The neodymium glass will be discussed first.

B. NEODYMIUM GLASS LASER

This laser is of the four-level type, as contrasted with the ruby three-level variety. An energy-level diagram of a four-level laser can be seen in Figure 1. It should be pointed out that there are radiationless transitions, both at the excited level and the lower level. These contribute nothing to the welding process, and only serve to trap energy in the laser itself. While the fluorescent emission actually is in the form of three bands with peaks at 8800, 10,500, and 13,500 Angstroms (Å), the 10,600 Å region is the most useful with respect to possible welding applications, and for that reason, is the only one shown on the transition diagram.

The emission lifetime is longest in the neodymium (Nd)-crown glass base, while lifetimes of one-third this amount are associated with the flint glasses, and lifetimes of only one-tenth that of Nd-crown glass are noted in lanthanum borate [2]. Long emission lifetimes are, of course, quite desirable for welding.

To summarize data relative to the prospects of using the Nd-crown glass base laser for welding, the following pertinent considerations are offered:

1. Nd-crown glass pumping is more effective with the rod at room temperature, than at LN_2 temperatures (77°K) [3]. (This does not eliminate the need for cooling, however, in a practical device.)

2. Barium crown glass permits the highest doping without lapsing into concentration quenching. This makes more ions available for radiation transitions, thereby giving higher output.

3. Conversion efficiency above threshold (point where lasing action begins) re-

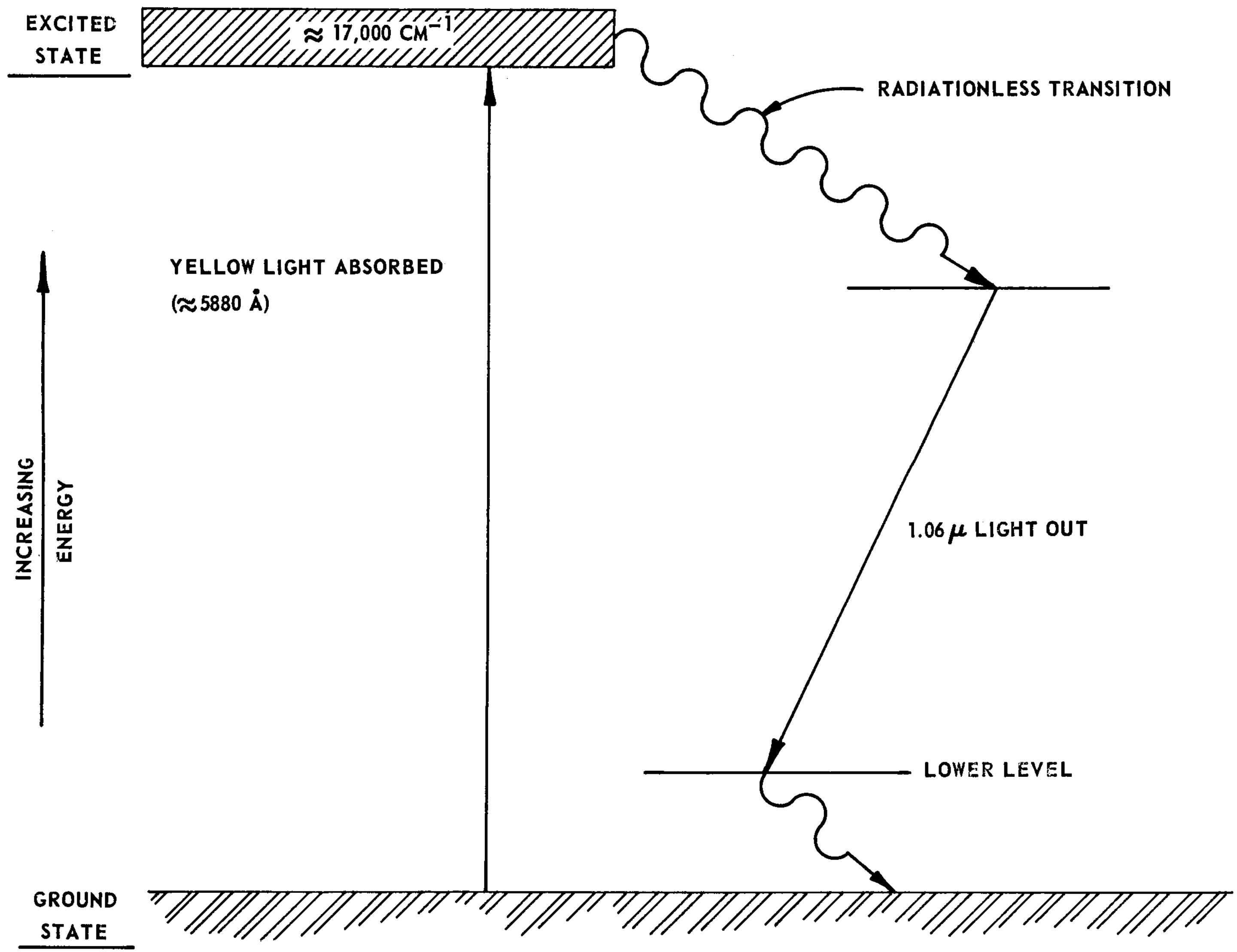


FIGURE 1. TRANSITION DIAGRAM OF NEODYMIUM GLASS LASER SYSTEM

ported to be around four percent, and threshold is only about half that of ruby [3].

4. Nd-crown glass can be manufactured in much larger sizes, and is generally much cheaper than ruby.

5. Barium crown glass has very low thermal conductivity, unfortunately, being on the order of 1.9×10^{-3} cal/ cm sec °C, which is much poorer than ruby.

6. The emission wavelength of 1.06 μ is less suitable for welding, from the point of view of reflectivity of the impinging beam. Reflectivity from typical welding condition aluminum using 1.06 μ laser light is about 75 percent; at 6943 Å it is about 65 percent.

7. At high pumping levels, the glass has a tendency to craze rather easily, and consequently, has rather limited life.

8. Unfocussed beam spread is about eight degrees, or greater.

With the advent of the Nd-crown glass laser it appeared for a time that the ruby lasers might be supplanted, but this has not actually been the case. In spite of some of these apparent advantages, the pink ruby is still probably the best high power laser today. Then too, actual operating Nd-crown glass systems do not always exhibit the improved performance noted under laboratory controlled conditions. Therefore, since ruby is still very important in laser development, the following is an evaluation of its potentialities for welding.

C. PINK RUBY LASER

Actually, as can be seen in Appendix A, there are two types of ruby lasers. The pink ruby rod is composed of Cr^{+++} Al_2O_3 with about 0.05 percent chromium ion doping. The red ruby rod is doped much heavier, approximately 0.5 percent. This heavy concentration produces what is known as satellite lines (satellites of the normal transition lines) which supposedly come about by the interaction and subsequent splitting of chromium ions [4]. The lines, as a matter of academic interest, occur at 7041 Å and 7009 Å, and are designated as N_1 and N_2. A decided disadvantage here is the need for very low temperature operation.

Pink ruby can operate at room temperature, but at room temperature the range of chromium concentration in the rod, in which laser action can be achieved at any pumping level, is very limited, and there are some severe heating problems with uncooled equipment for welding. The ruby laser is fundamentally a three-level laser (Fig. 2). The solid transition lines show the usual modus operandi. The dotted lines show possible transitions, but these must be gleaned, or extracted by special filtering, or other techniques, as the normal mode results in the 6943 Å output. Further, in most practical welding sys-

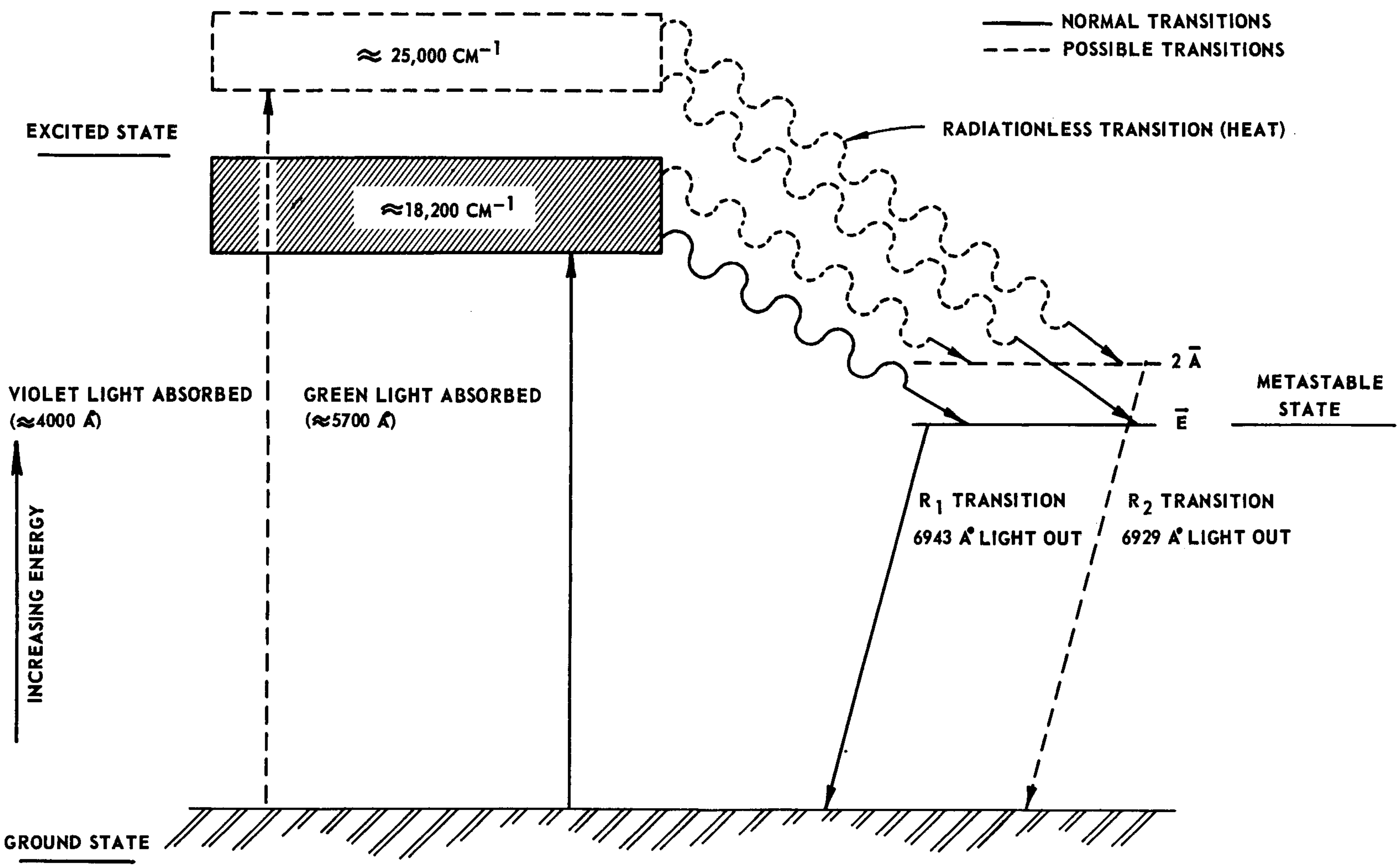


FIGURE 2. TRANSITION DIAGRAM OF PINK RUBY LASER SYSTEM

tems, the ruby rod would probably be adequately protected from violet and ultra-violet rays by a pyrex cover glass, as some sort of filter is usually desirable to prevent bleaching of the ruby. This greatly attenuates the pumping light needed to attain the 25,000 cm^{-1} excitation level.

The importance of ruby rod parameters can hardly be over-emphasized, as tremendous differences in large ruby quality have been observed in our experiments at the Marshall Space Flight Center (MSFC). Because it is so important, a sort of specification - general information sheet has been included in Appendix B.

The data presented are taken partly from work at MSFC, and partly from current literature. Test data at MSFC have indicated as much as 70 kilojoules (KJ) difference in threshold between similar rubies 0.625 inches in diameter. This would constitute a serious problem if rubies were carelessly exchanged in laser equipment. It also indicates the great difficulty the manufacturers have in controlling the quality of these large rubies Ruby problems however, constitute only a portion of the problems encountered in the operation of a complete ruby laser welding and drilling system.

SECTION III. MARSHALL SPACE FLIGHT CENTER 240 KJ SYSTEM

A. GENERAL

With the advent of the laser, it was apparent that a new, and radically different, high intensity heat source for metalworking operations was evolving. In consonance with the basic philosophy of maintaining a bench oriented technical capability, it was decided to engage in a limited activity to evaluate the new device for possible long range applications in MSFC space vehicle programs. Considerable development work in high intensity transient magnetic field generation for metalworking had already provided the majority of the basic data in pulse power systems, high voltage engineering, nano-second regime diagnostics and other areas peculiar to high field and laser work. An additional inducement was the fact that most of the required laser apparatus was already available, or could be employed on a prescheduled basis. The only remaining requirement was the development of the laser gun.

B. FUNDAMENTAL LASER GUN CONSIDERATIONS

Considerable confusion exists regarding excitation geometries, or guns, for lasers. Early designs favored the coaxial geometry, or the close coupled geometry [9 and 10]. Later studies caused a flurry of interest in the elliptical geometry [11]. Three typical high powered gun types can be seen in Figure 3. The type gun required is probably best determined by the intended use of the laser. At MSFC the coaxial geometry was selected for the following reasons:

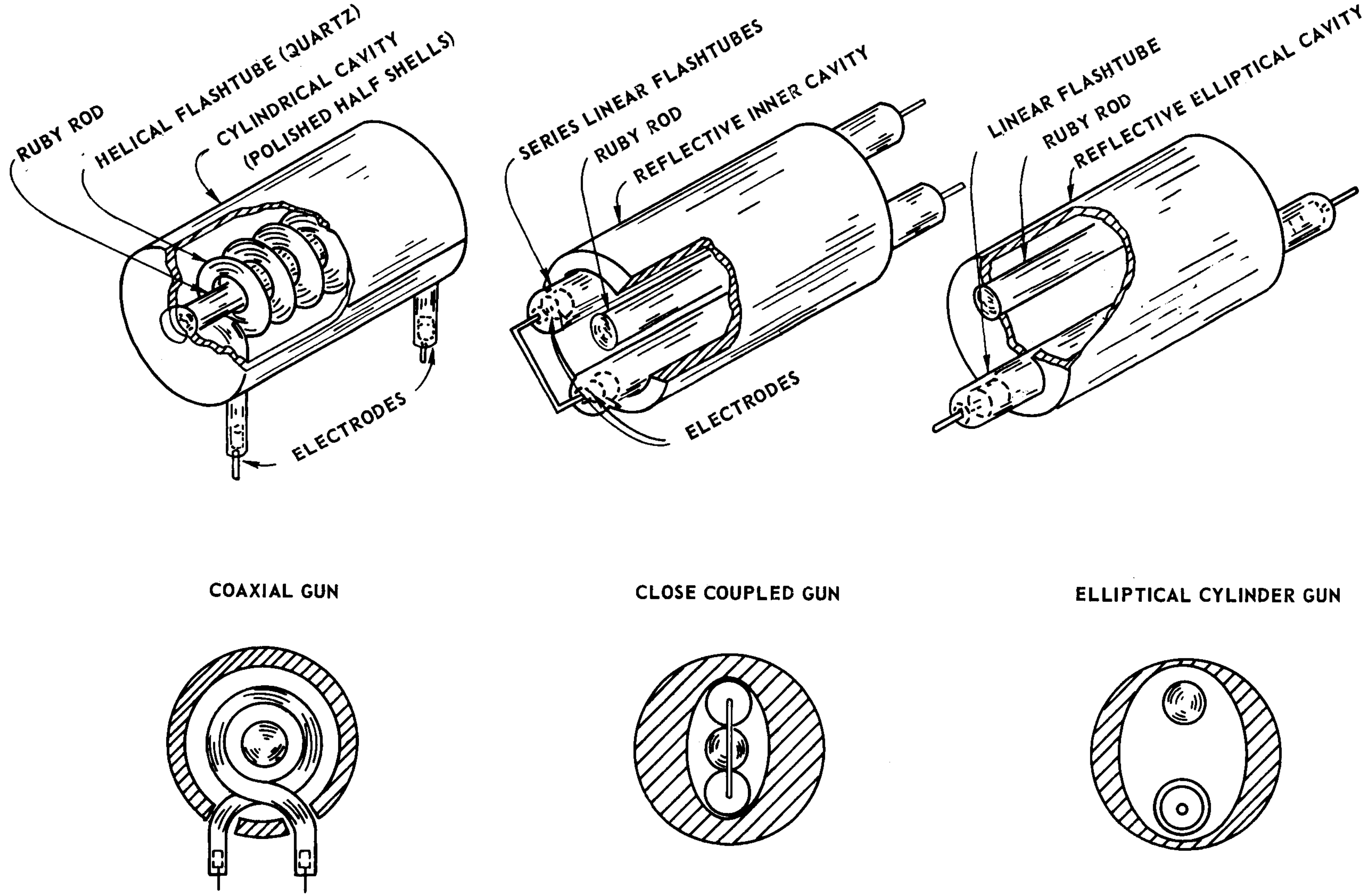


FIGURE 3. TYPICAL HIGH POWERED LASER GUN DESIGNS

1. The helical flashtube seemed to be the only type tube potentially capable of withstanding the plasma shock wave and heat flux associated with the 240 KJ discharges contemplated. Linear tubes still exhibit difficulty in the 30 to 40 KJ range, and the mortality rate is rather high [12]. It is true that linear tubes can be arranged in series, but there is a limit to that, also. Studies have shown that there is an optimum number of elliptical cavities for the elliptical gun (approximately four). Even at 40 KJ, this would only have provided a 160 KJ capability.

2. The elliptical cavity guns effect a strong focussing action in the central region of the rod, which facilitates inversion, and in effect, lowers the threshold, or point where lasing begins; but, the bulk of the rod, especially if it is large, remains relatively unpumped, so that for operation above threshold the output appears to be far superior for the coaxial cavity gun, as had been suspected [13].

3. The coaxial system is easier to cool than the close-coupled gun.

4. The coaxial gun cavities do not have to be specularly reflecting, only reasonably well polished (aluminum seems to be satisfactory). Elliptical cavities have to be specularly reflecting, which creates additional problems at very high energy density.

Figure 4 shows the coaxial gun with top cavity reflector removed. However, in spite of the coaxial geometry advantages, there have been some problems. Some tubes have exhibited a tendency to fail in the general seal area (Fig. 5). In addition, mounting of the flashtube "legs" is quite critical regarding stresses introduced by poorly fitted mounting clamps. Mounting in a relatively unstressed condition is essential. Complete specification data on the coaxial tube used at MSFC can be found in Appendix C. Exhaustive tests were conducted before a satisfactory high energy tube was developed by the manufacturer.

In designing the flashtube system, damped oscillatory operation was carefully avoided. Initially, external resistance was provided to avoid this, but when the tubes were tested, it developed that the tube resistance did not drop much below two ohms during the conduction phase. Using the 300 μh pulse forming choke, this value alone was sufficient to prevent oscillation. The dynamic resistance of this large tube can be seen in Figure 6. A fairly complete analysis was made in an MSFC report [14]. In addition, Schawlow's double pulse technique was tested regarding cushioning the shock on the flashtube, and increasing the light output. A low energy pulse preceding the main discharge by 130 microseconds was tried. However, to maintain the proper pulse width for the ruby, some inductance was required, and under these conditions, the technique did not seem to help much. Most of the flashtube problems have been resolved reasonably well, though, and current emphasis is on focussing systems.

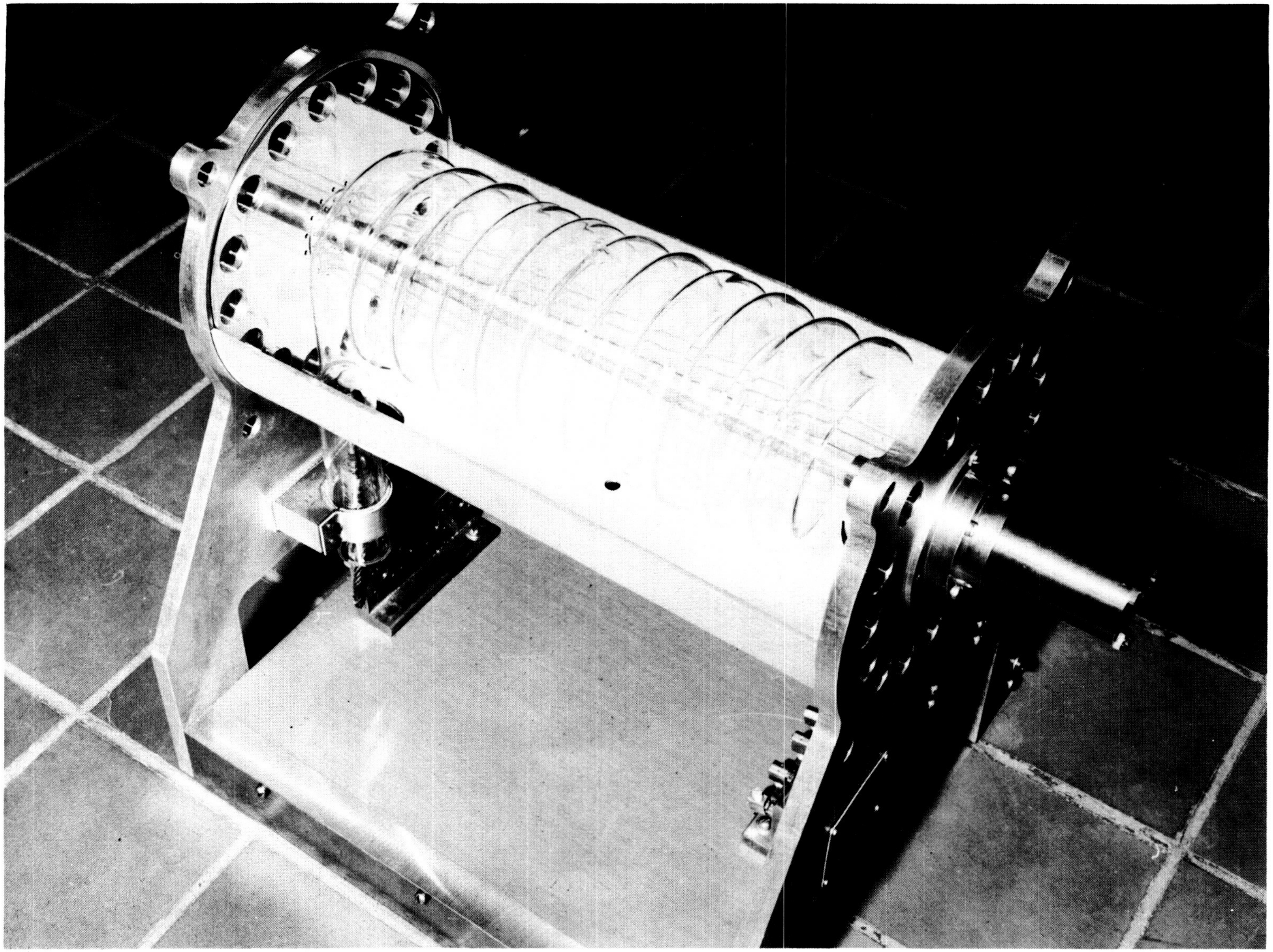


FIGURE 4. 240 KJ LASER GUN WITH TOP CAVITY REFLECTOR REMOVED

FIGURE 5. FLASHTUBE FAILURE IN END SEAL AREA ON 240 KJ SHOT

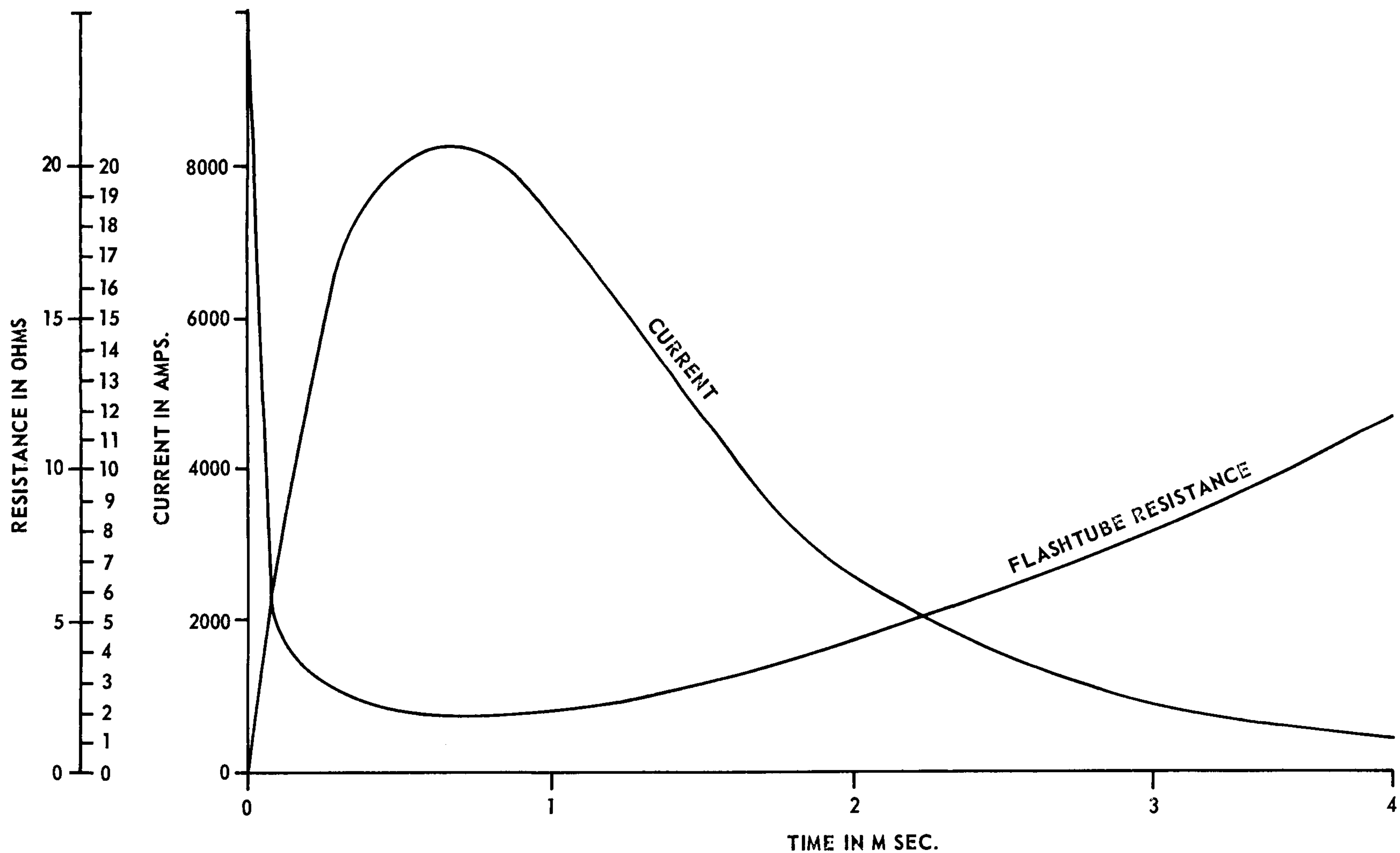


FIGURE 6. FLASHTUBE DYNAMIC RESISTANCE AND CURRENT MSFC 240 KJ LASER

C. FOCUSSING SYSTEM DETAILS

Shortly before the 240 KJ laser system was begun, a small 4000 Joule (J) commercial system was tested and evaluated in foil welding applications. During this program, focussing system problems became abundantly evident. This would be attested to vigorously by one metallurgist at MSFC, most of whose microscope objective lenses now have very neat holes drilled through them! At any rate, power densities obtainable from lasers can easily exceed those of the electron beam by an order of magnitude, or two, and this is quite sufficient to drill anything - even diamond. Cemented lenses were destroyed immediately. The only material that proved satisfactory in the configurations employed was quartz. At present, however, a number of manufacturers have lense assemblies as integral parts of fairly high powered systems that apparently are quite satisfactory, and lenses are not nearly the problem they once were. But, they still remain a problem for energy output of approximately 2000J.

Two basic types of lense arrangement are being developed for the 240 KJ system:

1. A fairly straight-forward double lense arrangement.
2. A Cassegranian arrangement.

Figure 7 shows the double lense arrangement. As a matter of academic interest, the holes in the end plate allow the rapidly heated air and LN_2 vapor to escape during the discharge phase.

Figure 8 depicts the Cassegranian arrangement, with a strainless steel impingement plate placed at the focal length, about 24 inches away. The Cassegranian arrangement has been employed for years by astronomers, but it should be pointed out that in this case, the system is, in effect, operated in reverse (Fig. 9). In the astronomer's telescope the light rays impinge on the large convex (primary) mirror, and are then focussed on the small (secondary) mirror. For the welding system, the laser beam is projected through the large mirror to the small spherical mirror (primary) which then reflects the beam to the large ellipsoidal mirror (secondary), which, in turn, focusses at approximately 24 inches. It is hoped that the energy density can be kept well below the point of ionizing the air, or rupturing lenses, by this technique. Both methods are undergoing tests at present. In the Cassegranian arrangement, the primary mirror (small spherical) has presented a problem. Even unfocussed, the beam evaporates the reflective coating almost instantaneously at an output of 1000 J or more. Primary mirrors of solid material will be tested shortly in an attempt to eliminate this problem. Most of the problems with the overall system are associated with the tremendous instantaneous power generated.

D. MEDUSA POWER SUPPLY AND PULSE FORMING NETWORK

Power for the testing of the 240 KJ system comes from a large capacitor bank facetiously referred to as "Medusa." The system was designed initially for intense transient magnetic field work, as noted previously, but has proved to be remarkably versatile,

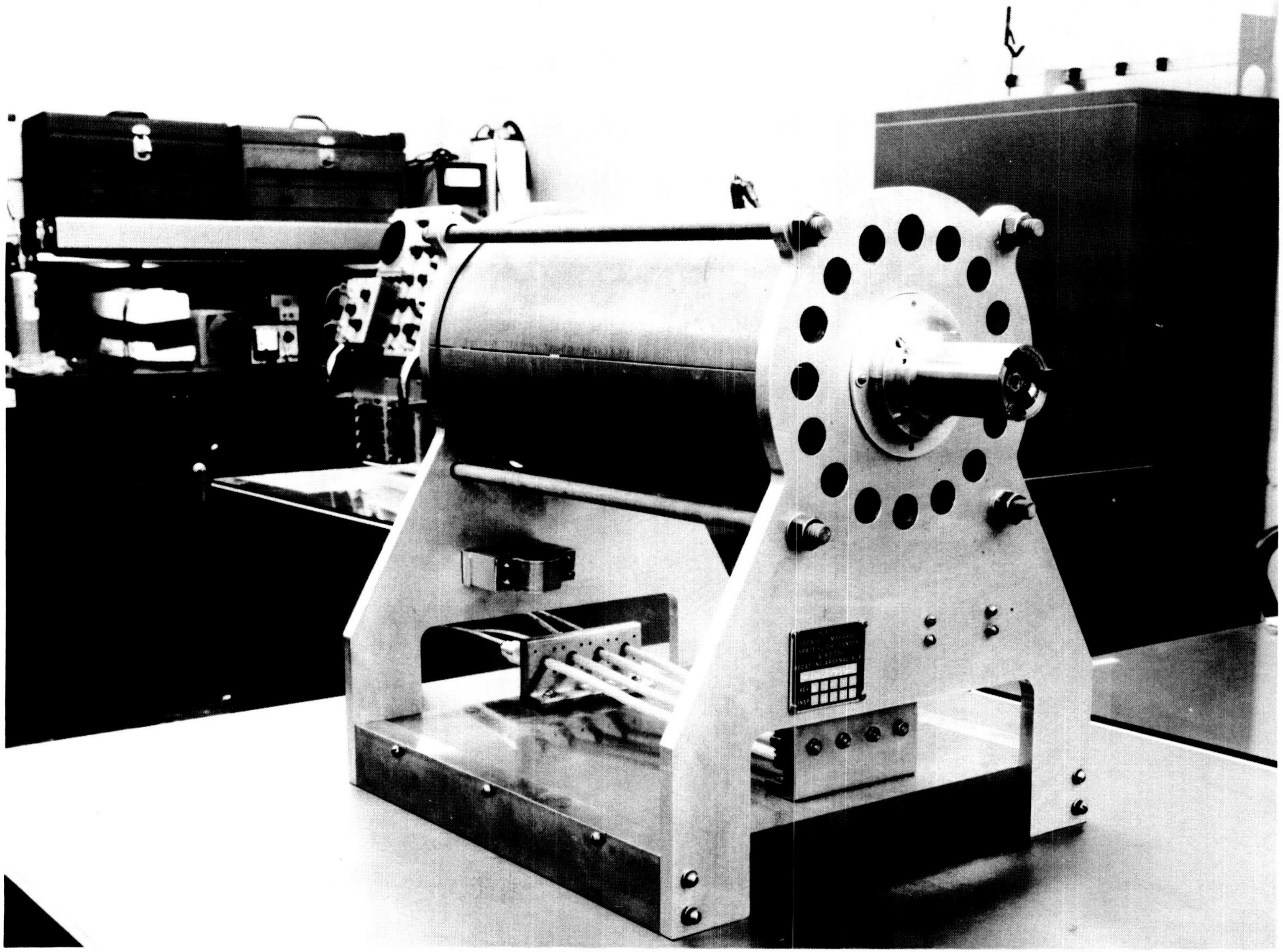


FIGURE 7. 240 KJ LASER GUN WITH DOUBLE-LENSE ATTACHMENT

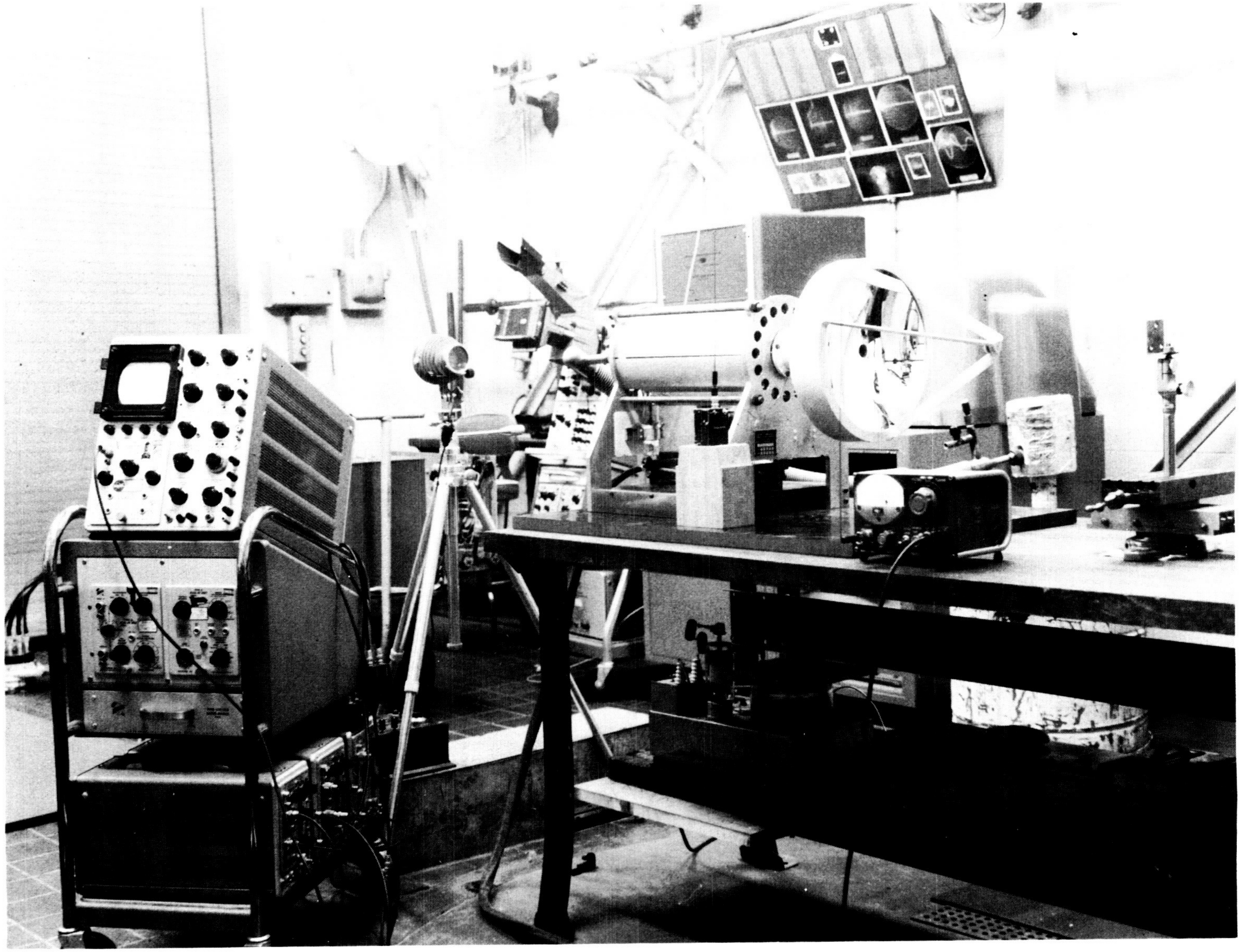


FIGURE 8. TESTING OF CASSEGRANIAN FOCUSSING ARRANGEMENT

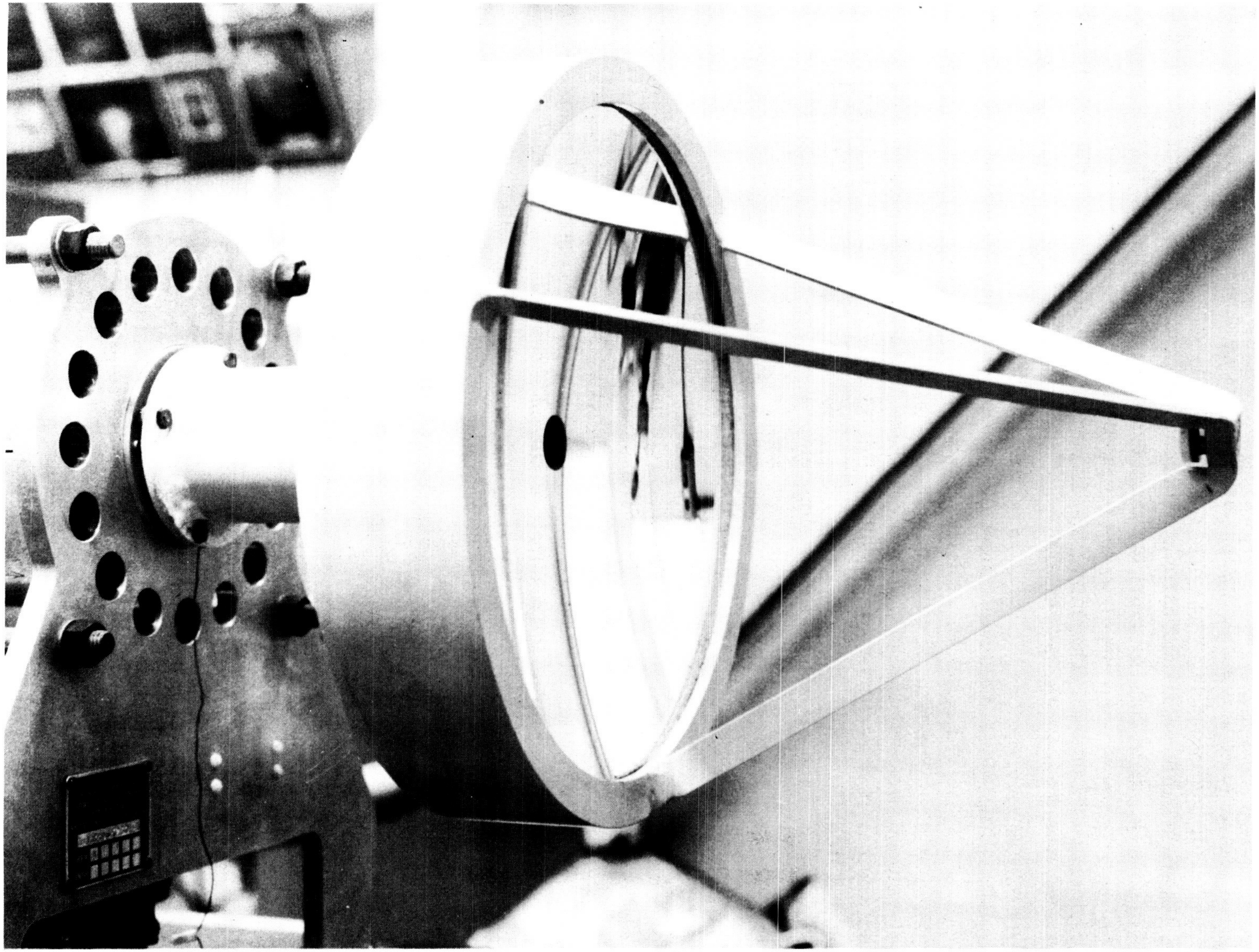


FIGURE 9. CLOSE-UP OF CASSEGRANIAN ARRANGEMENT

and also adaptable to laser work. The bank is conveniently subdivided into ten 24 KJ elements, each controlled individually by a separate pulse delay generator. It is possible to discharge all elements simultaneously; or, the elements can be delayed to effect a modulated output. This technique is to be employed in investigating the effects of pulse length and pulse repetition rate on the formation, undercutting, and aspect ratio of the weld bead. Figure 10 shows the main control panel of the Medusa pulse power system. A special pulse forming network was developed to assist in obtaining the proper electrical discharge waveshape into the flashtube. The entire laser system study has been approached from the laboratory apparatus aspect, with a high degree of experimental flexibility uppermost in mind. The primary objective still remains a basic evaluation of beam effects in materials (welding and drilling), with no development of actual production equipment contemplated. This is apparent again in Figure 11, which shows some of the pulse forming network component development activities. Obviously, much smaller choke coils of 300 μh inductance could be developed for operation at 20,000 volts, but this is a development program in itself, and would only serve to provide additional delay in actually applying the high energy density pulses in drilling and welding. Figure 11 also indicates some of the specialized diagnostic apparatus required in laser development.

E. DIAGNOSTICS AND DATA

One of the big difficulties with the pink ruby laser regarding potential welding applications is the tendency for the output to fluctuate. This is due to many factors such as heating, ruby stresses, changing optical pumping effectivity because of vapors, frost, and other less dominant effects. Before these variables can be controlled, more specific data are required. This implies an accurate means of measuring light output. One of the most successful techniques used so far has been the "rat's nest" calorimeter. This device consists of about 1000 feet of very fine wire in a random jumble, or rat's nest, which is then ensconced in an evacuated dewar. An aperture is provided for the beam to impinge, and the beam gives up its energy to the wire. The wire constitutes one arm of an ordinary wheatstone bridge circuit, so the unbalanced condition created by the increased resistance of the wire is translated into total output energy by a suitable calibration factor. Figure 12 shows the development of the calorimeter, using the small 4000 J gun as a beam source. This type of output measuring device is now available commercially. When attempting measurements of output energy in the 2000 J range, a beam splitter with an attenuation factor of about 1000 is required, as the output energy is much too strong for ordinary calorimeters with 5 to 10 J measuring capability. Figure 13 depicts measurements of output being made on the 240 KJ system. Specific output data and the output curve can be seen in Appendix C. Figure 14 is a photograph of a projected, unfocussed beam at approximately 150 KJ energy input level. Spot diameter-distance measurements indicated beam divergence on the order of 30 seconds of angle. Careful examination of the unfocussed spots (burned areas and holes) revealed possible non-uniformity of energy density over the spot cross sectional area. Although presumably of less direct consequence in a focussed spot, it did imply some variation in the lasing mode from shot to shot. It was not feasible to look in the 2000 J, 0.625 inch ruby's eye, so to speak, but a 0.250

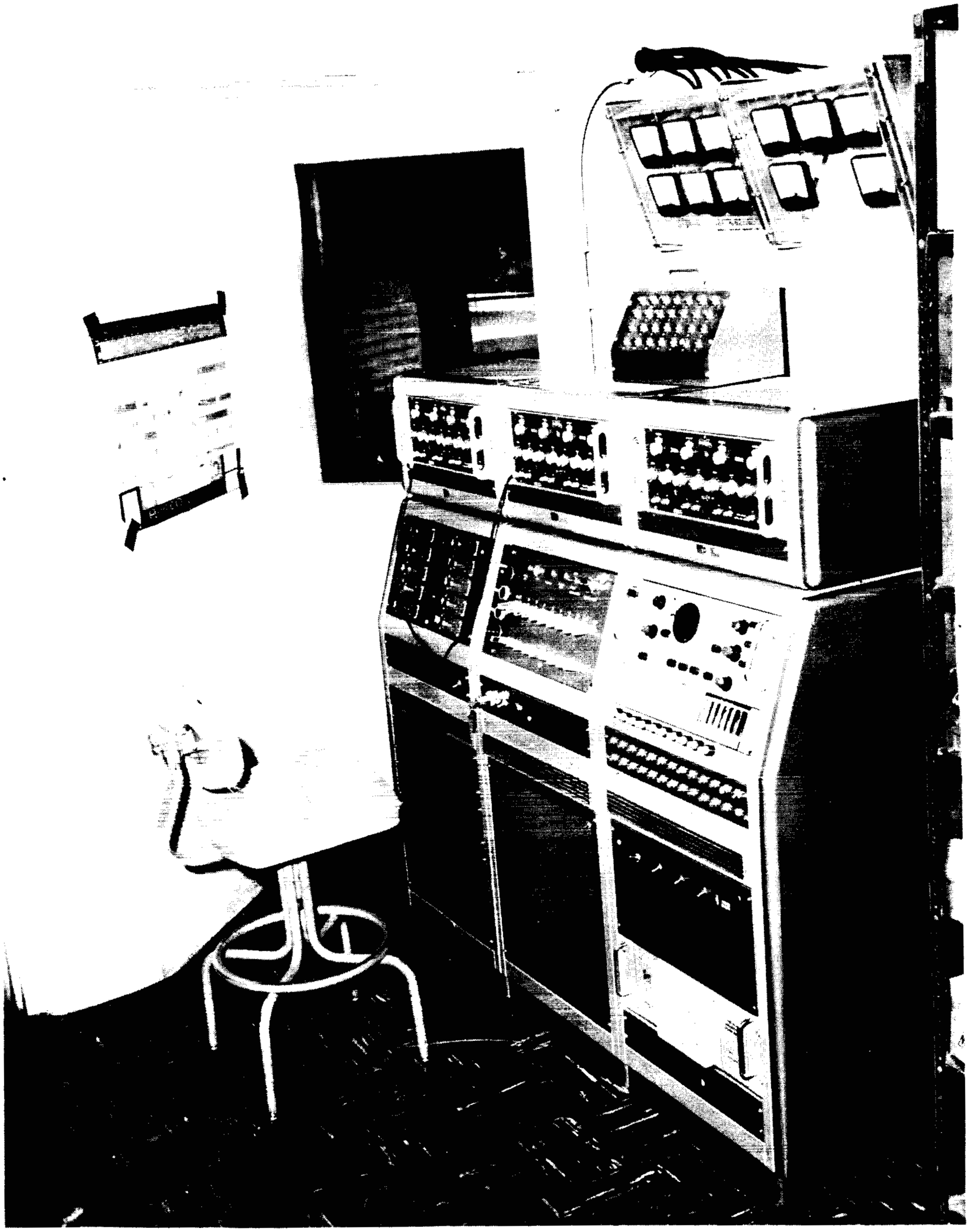


FIGURE 10. MEDUSA PULSE POWER SYSTEM CONTROL PANEL USED IN LASER EXPERIMENTS

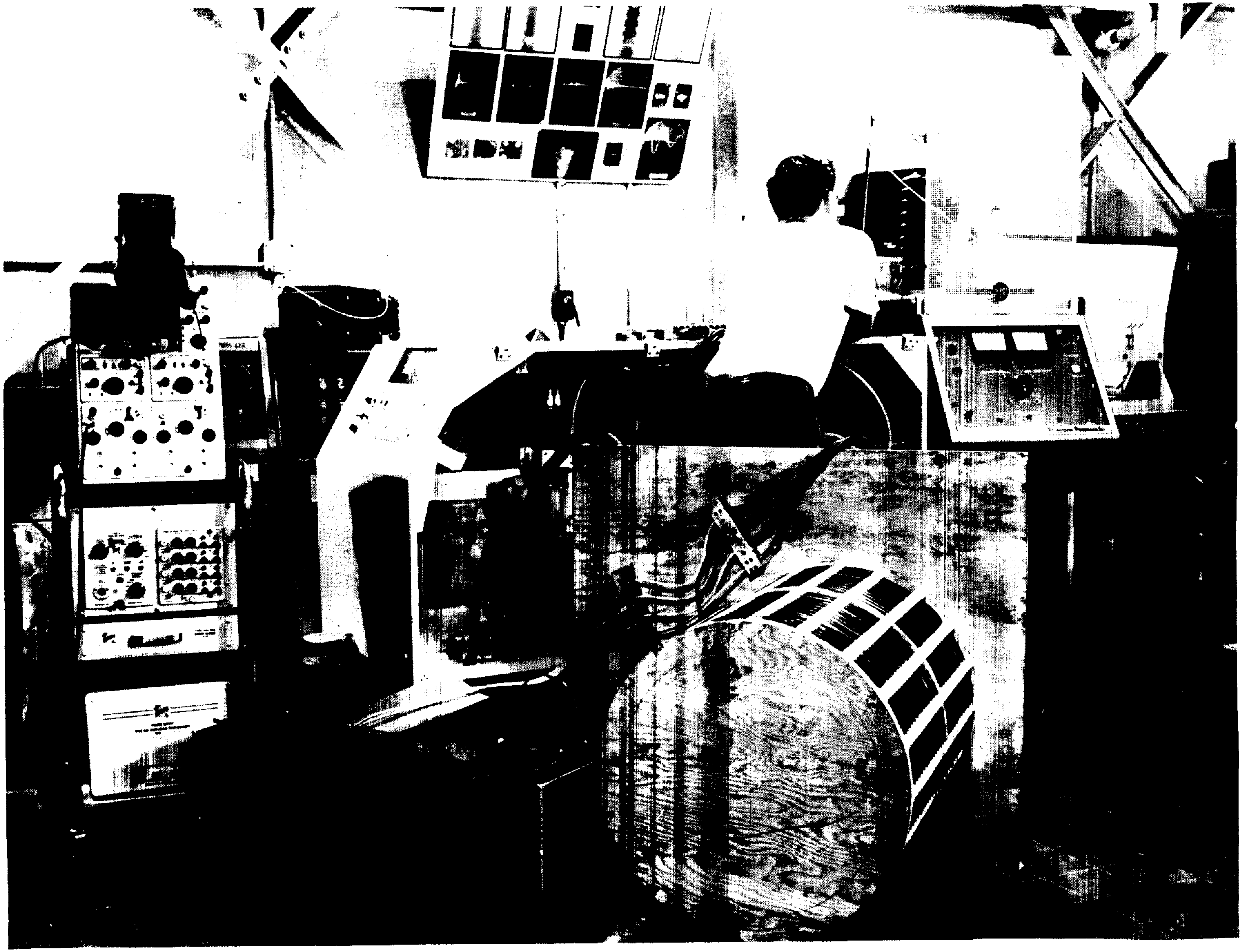


FIGURE 11. LASER PULSE FORMING NETWORK COMPONENT DEVELOPMENT

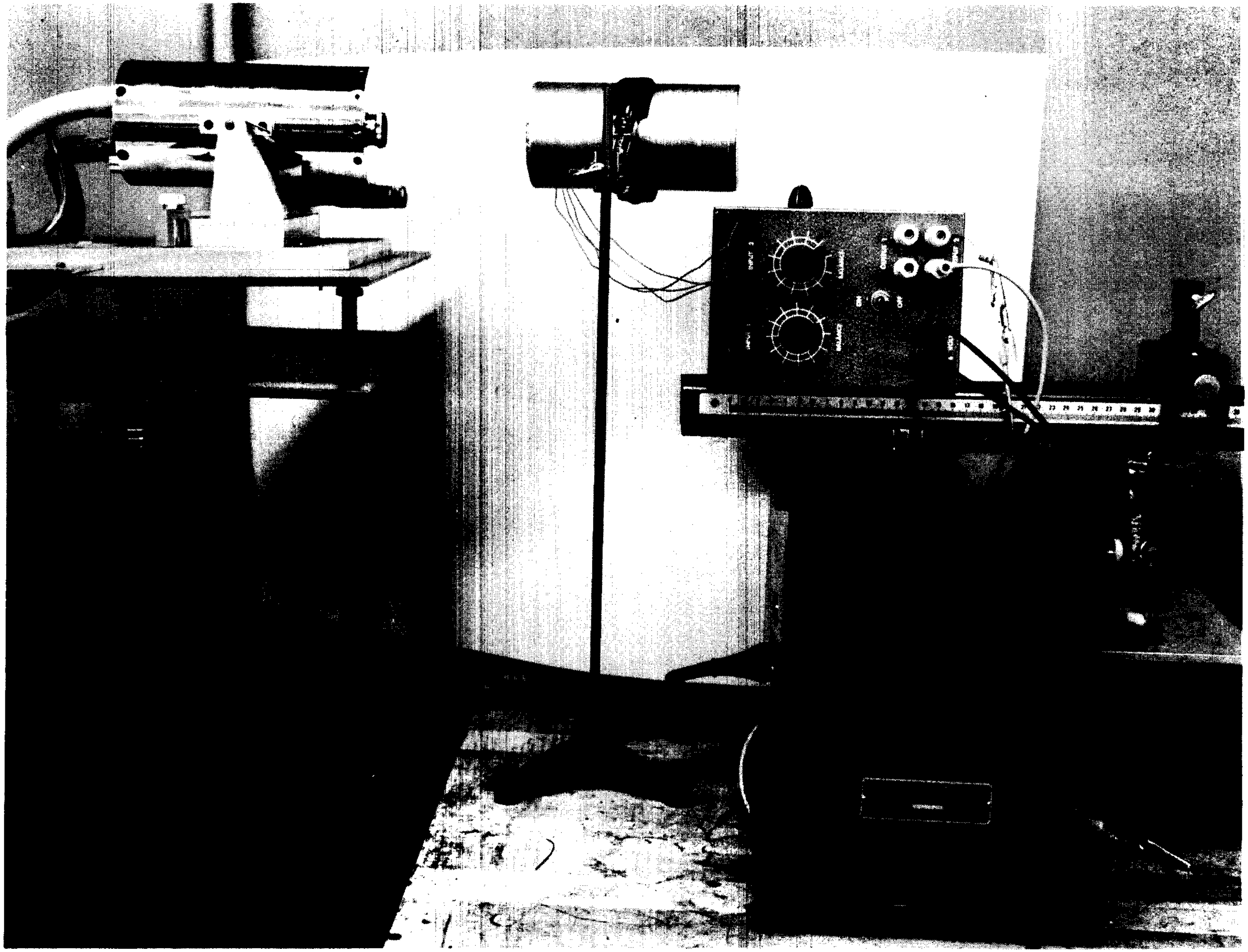


FIGURE 12. RAT'S NEST CALORIMETER DEVELOPMENT FOR MEASURING LASER OUTPUT

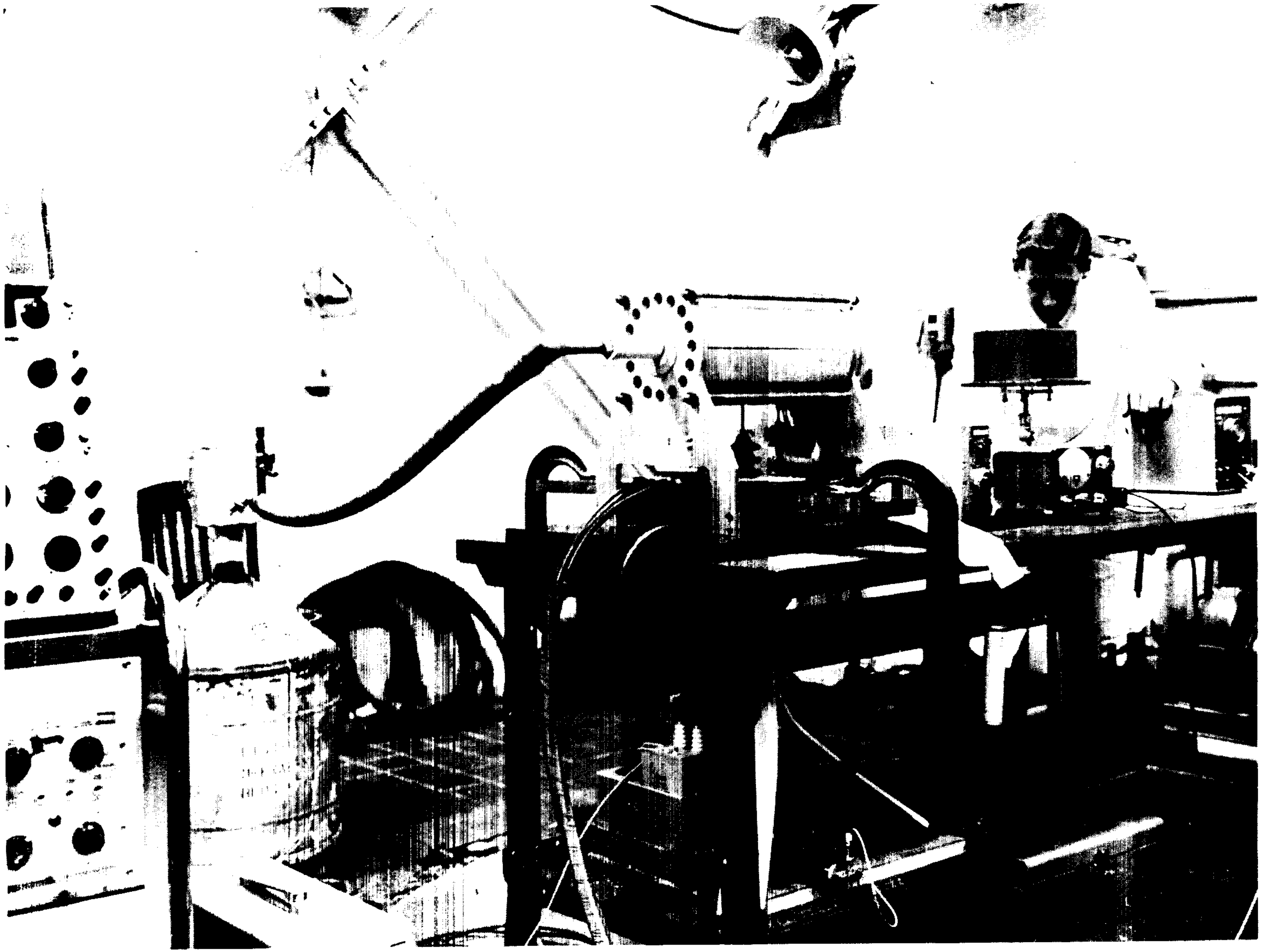


FIGURE 13. 240 KJ LASER OUTPUT MEASUREMENTS

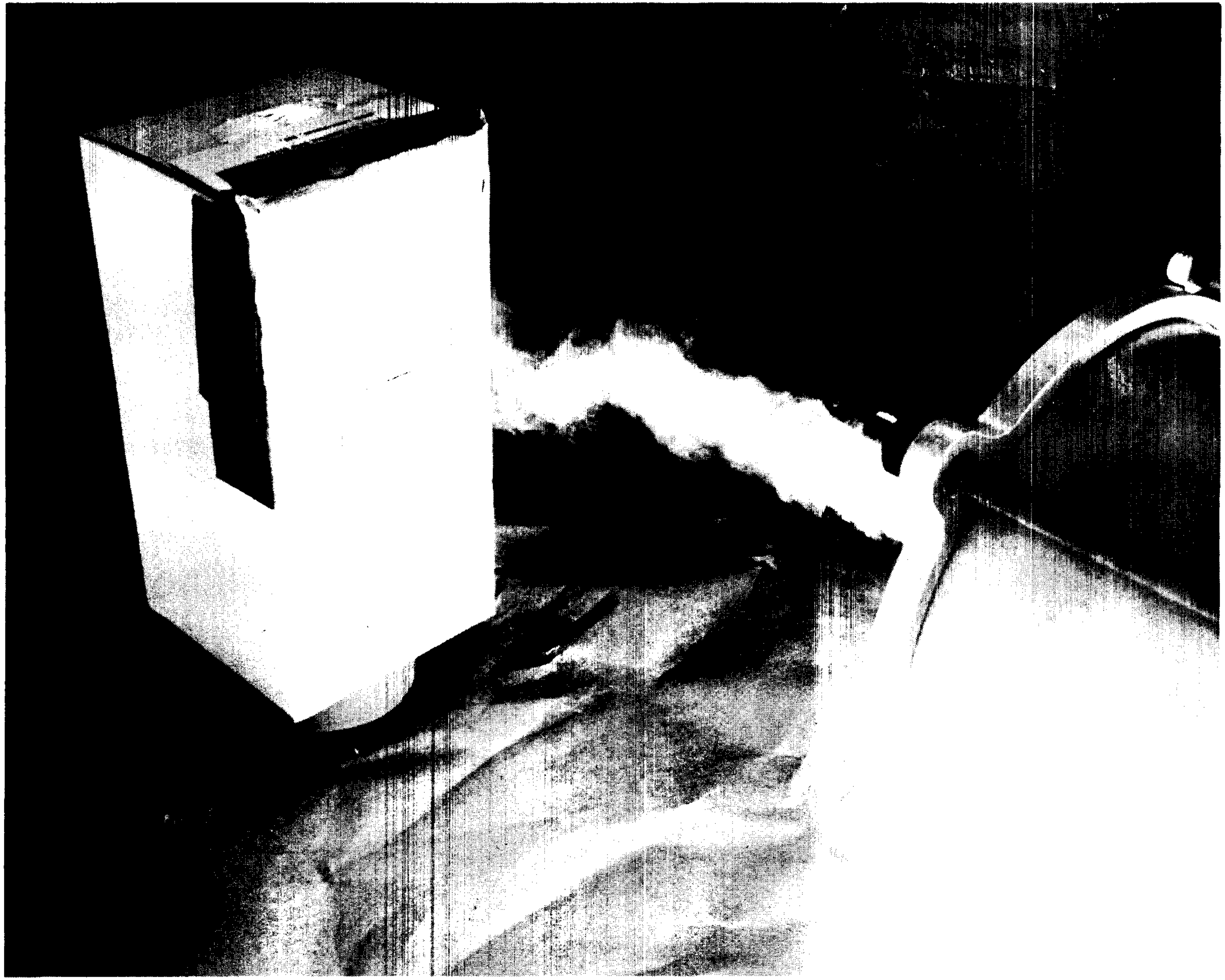


FIGURE 14. 150 KJ UNFOCUSSED LASER BEAM

inch ruby operating just above threshold was observed in an effort to examine this apparent power density fluctuation. An STL image converter camera was used to photograph the ruby directly, during lasing. Figure 15 depicts the test setup, and Figure 16 shows the output radiation varying with time and position across the crystal face. This selective filament lasing has received a lot of attention to date, but apparently no positive control techniques have evolved, and good agreement on cause, etc., has not been reached. Judging from results obtained on the 4000 J system, this phenomenon does not appear too detrimental in focussed spots, but it probably cannot be considered a beneficial effect either. What fluctuations in focussed spot density to expect, if any, remain to be determined for the 240 KJ unit.

SECTION IV. WELDING ASPECTS OF LASER

A. GENERAL

Currently, the laser has been rather well accepted in the microwelding field. Repeatability of settings, the capability of joining dissimular materials of widely different thicknesses, and operation in air, have proved particularly attractive in this field. Since, in some cases, no pressure need be applied to the joint, physical displacement does not result. Occasionally, however, separation occurs between the faying surfaces. This was observed when welding foils with the 4000 J commercial unit mentioned previously. Although the power density is very high in the well-focussed laser spot, there is still some thermal distortion whenever repetitive pulses are required to produce a weld of any appreciable length, rather than a spot. In these studies, butt joints were made in the following materials:

1. 304 stainless steel, 0.008 inch thick
2. 5086 aluminum, 0.005 inch thick
3. 2219 aluminum, 0.005 inch thick

The output of the laser was about 2 J with an input of 4 KJ. The efficiency was 0.05 percent. On the limited number of welds made using 304 stainless steel no cracking was evident, although the welds were made with a pulse repetition rate (PRR) of about 0.08 pulse per second. Attempts to weld either 5086 aluminum or 2219 aluminum were unsuccessful, evidently because of oxide formation problems. Conventional shielding gas precautions probably would have eliminated this problem, but a very small evacuated box was used instead. Satisfactory aluminum welds were made in this manner by projecting the beam into the box through a piece of good quality glass which comprised one of the walls of the box. Apparently, owing to losses in transmission and other factors, no appreciable difference in energy was required to weld stainless steel in air compared with aluminum in the chamber, or box. With the low volume of material in the box and at the PRR noted previously, vapor deposition was not much of a problem on the glass. Higher power and greater material volume melted could be expected to result in vacuum deposition conditions similar to those experienced in electron beam welding. The vacuum experiment was

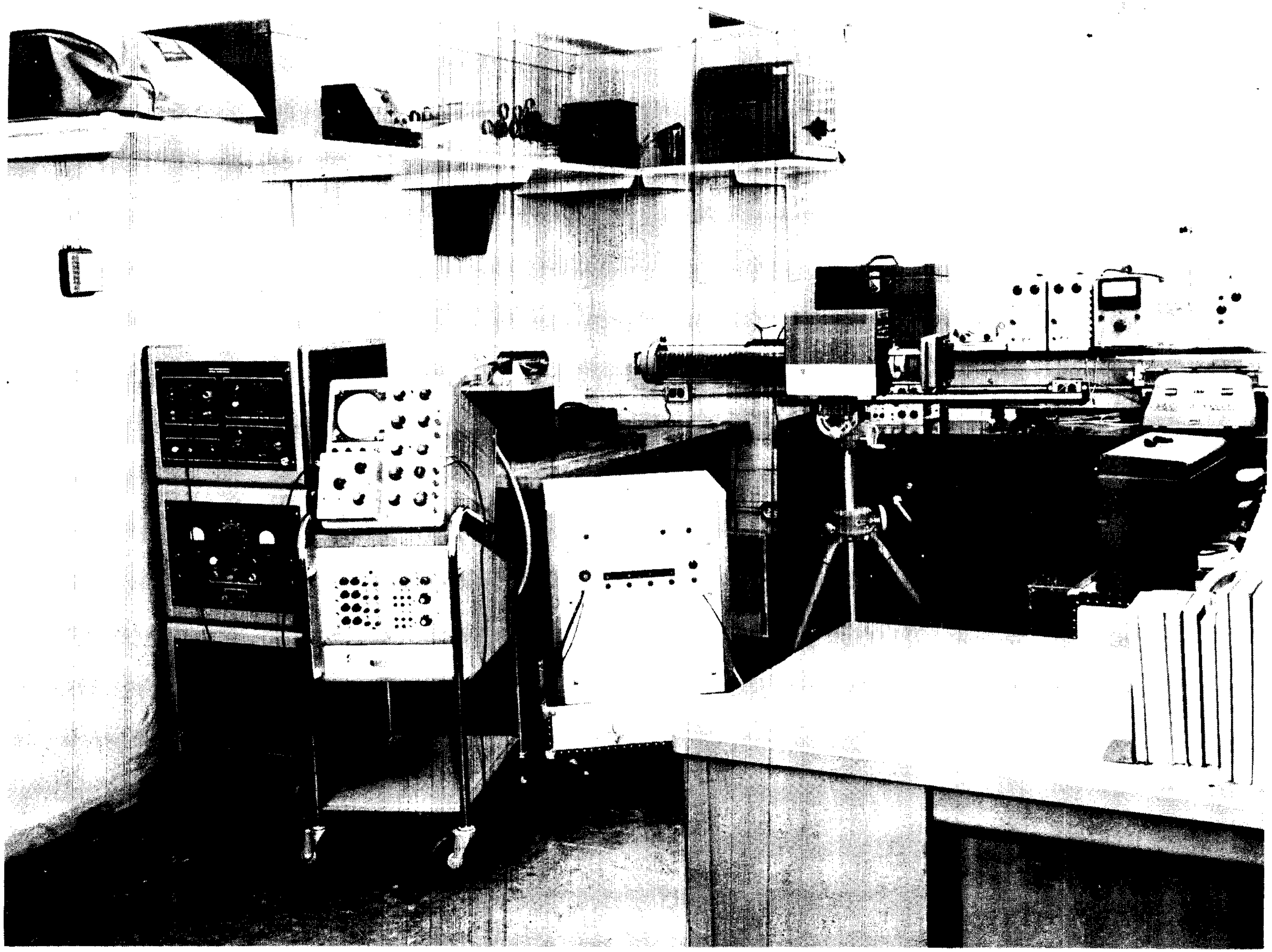


FIGURE 15. OBSERVATION OF RUBY FILAMENTARY LASING MODES

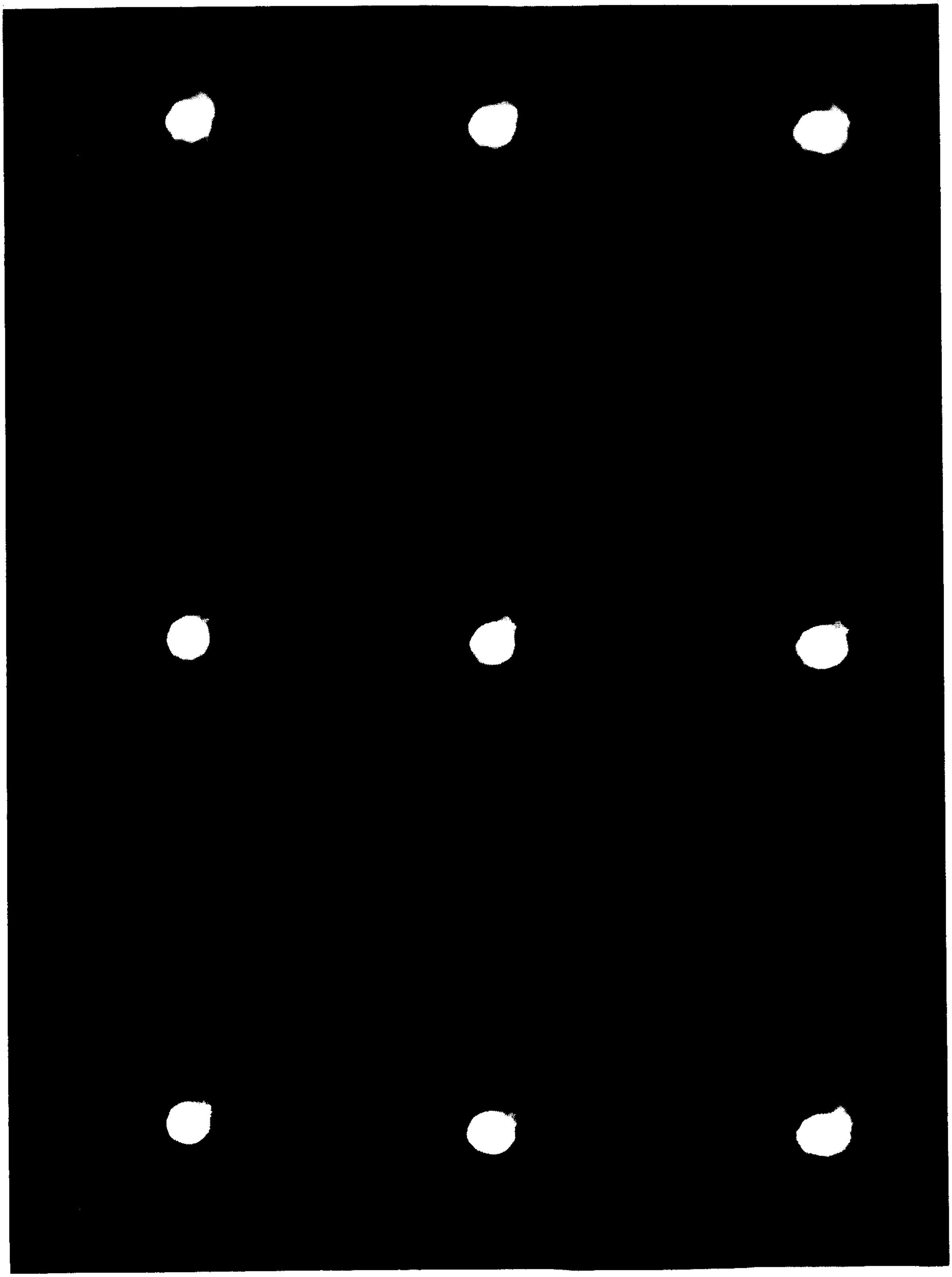


FIGURE 16. RUBY OUTPUT RADIATION VARIATION WITH TIME AND POSITION ACROSS CRYSTAL FACE

of interest because of the implications associated with projecting a working beam from a shirtsleeve environment into a vacuum, or space environment. This is a unique capability associated only with the laser at present. Figure 17 shows a small butt weld in 304 stainless steel in progress. The goggles worn by the engineer are supposed to filter red light to protect the individual's eyes. Extreme care should be exercised in the use of the system because of the potential danger to the human eye. Investigators have since found that even reflected laser light can be harmful under certain conditions.

Figure 18 shows one of the welds made in 304 stainless steel. Even with only 2 J input, disruptive surface conditions could be crated by too sharp a focus - that is, power density too high. By focussing well below the top surface of the foil, much better results were obtained. It should be mentioned, however, that the general complexion of the weld changes markedly with change in PRR and in pulse width. About half the weld in Figure 18 was made single pass only, while the other half was made by resorting to two passes.

B. Q-SPOILING TECHNIQUE

The so-called "Q" spoiling technique used to increase the instantaneous output power actually is detrimental to the welding process. In this case, much higher instantaneous power is generated, but the total energy delivered is less. This high instantaneous power causes excessive vaporization which results in drilling action, rather than melting. Power densities in excess of 300,000 watts per square centimeter will result predominantly in vaporization of the aluminum. Figure 19 shows the auto-collimation operation associated with the alignment of a Kerr Cell for Q spoiling experiments. The Kerr Cell contains the radiation, allowing it to build up to a higher instantaneous peak before it is released by a voltage pulse on the cell; the cell performs as a sort of gate, or shutter.

While the Q spoiled pulses in the 50 nano-second region are of much interest for communications applications, this seems now to be a step in the wrong direction for welding applications.

C. PRR AND PULSE WIDTH

The question of PRR and pulse width (PW) is very interesting but is probably not completely understood. Oddly enough, some very pertinent welding information is gradually evolving from NASA studies of meteoroid simulation using lasers. Studies of momentum transfer and cratering effects produced by Q spoiled, or giant pulses, as contrasted to normal pulses have shown that momenta produced by normal laser pulses depend on the thermal properties of the target material [15]. The momentum due to the incidence of a giant pulse is greater than that due to a normal pulse, and the velocity of material efflux is much higher for giant pulse impacts than for normal laser impacts. Neuman contends that the distribution of the laser energy over several component pulses occurring over a relatively long time interval causes more energy to be used for melting and less for evaporation. The complete theory evidently is not completely worked out, but the

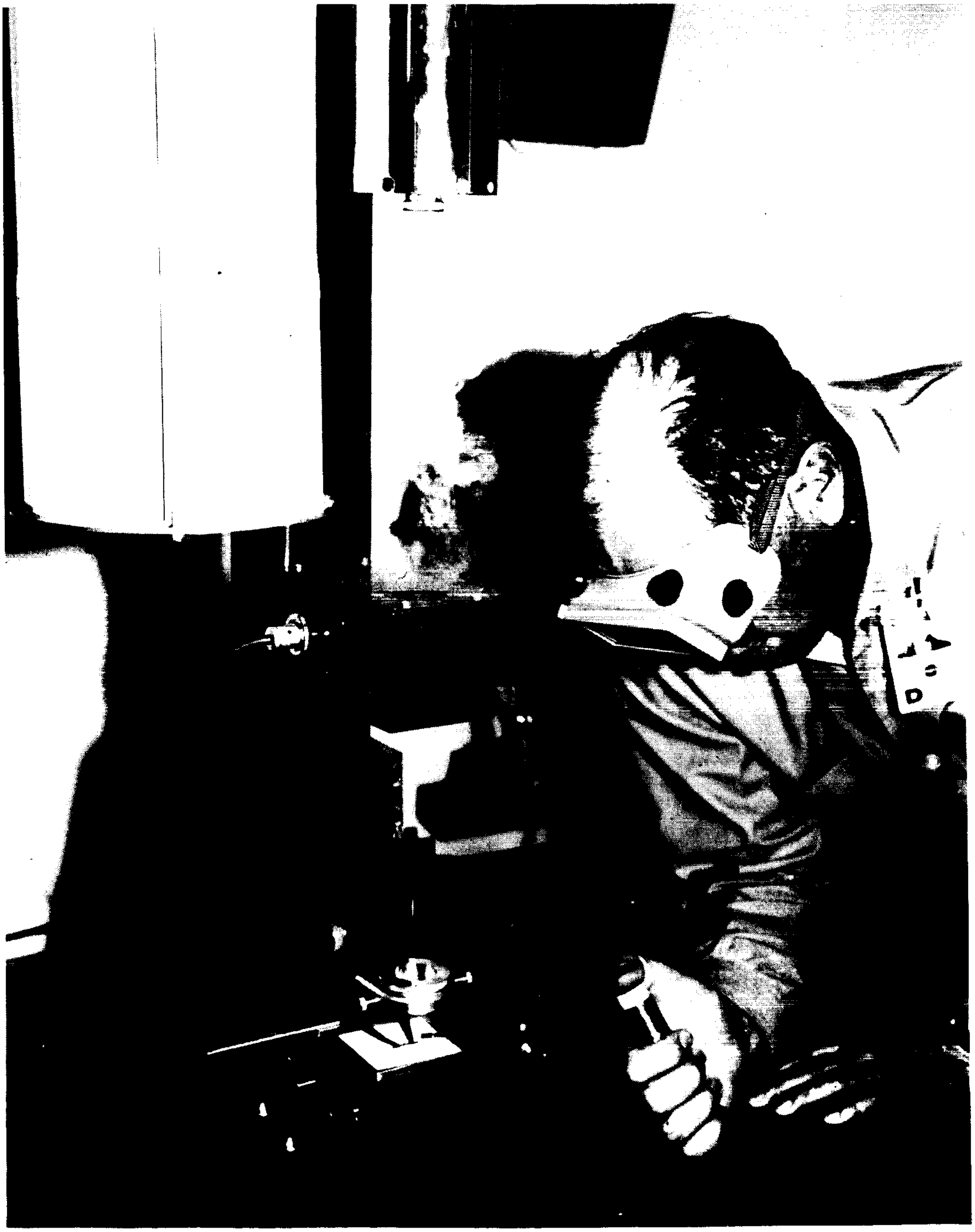


FIGURE 17. 4000 J PULSED LASER WELDING 304 STAINLESS STEEL

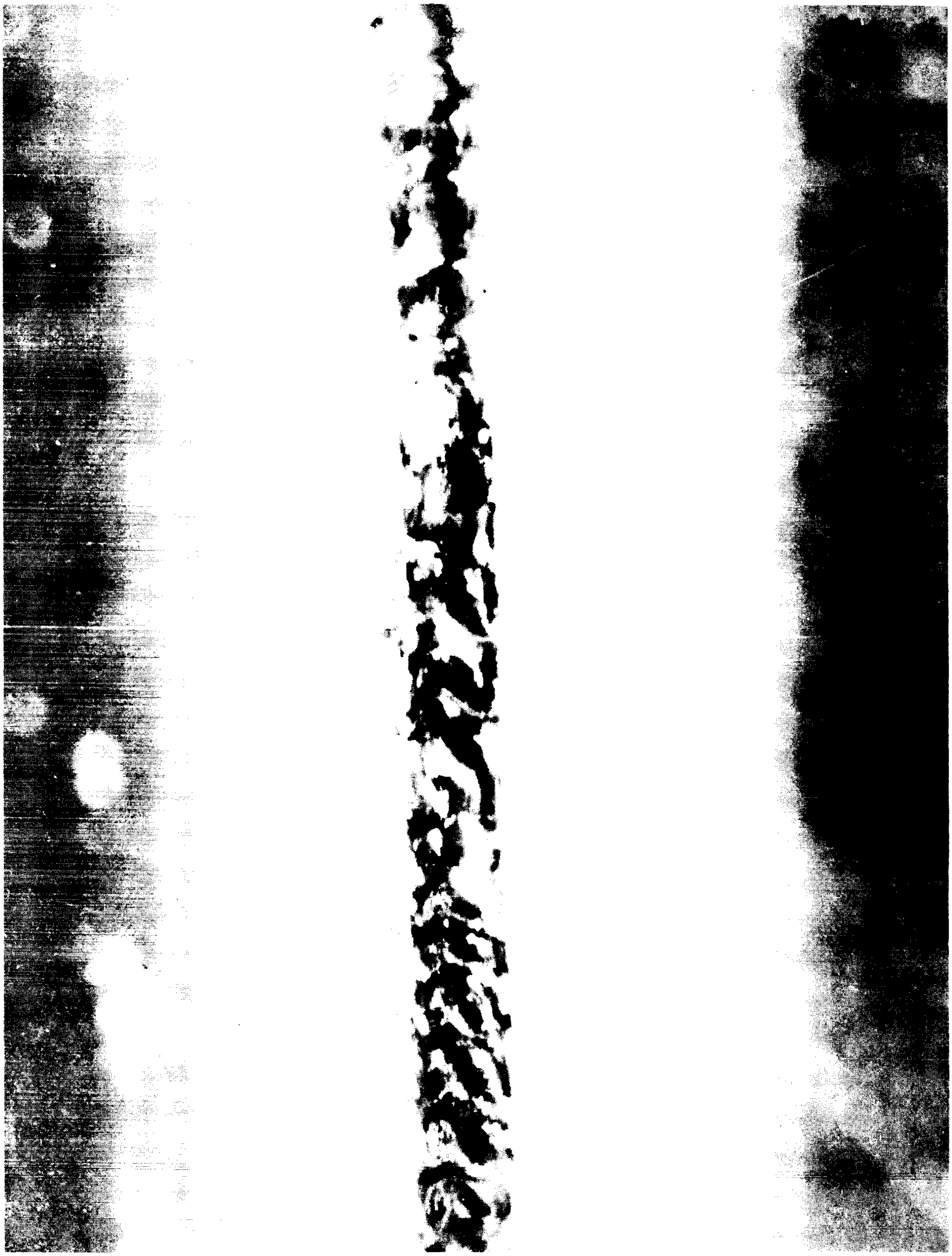


FIGURE 18. ONE AND TWO PASS LASER WELD IN 0.008 INCH STAINLESS STEEL

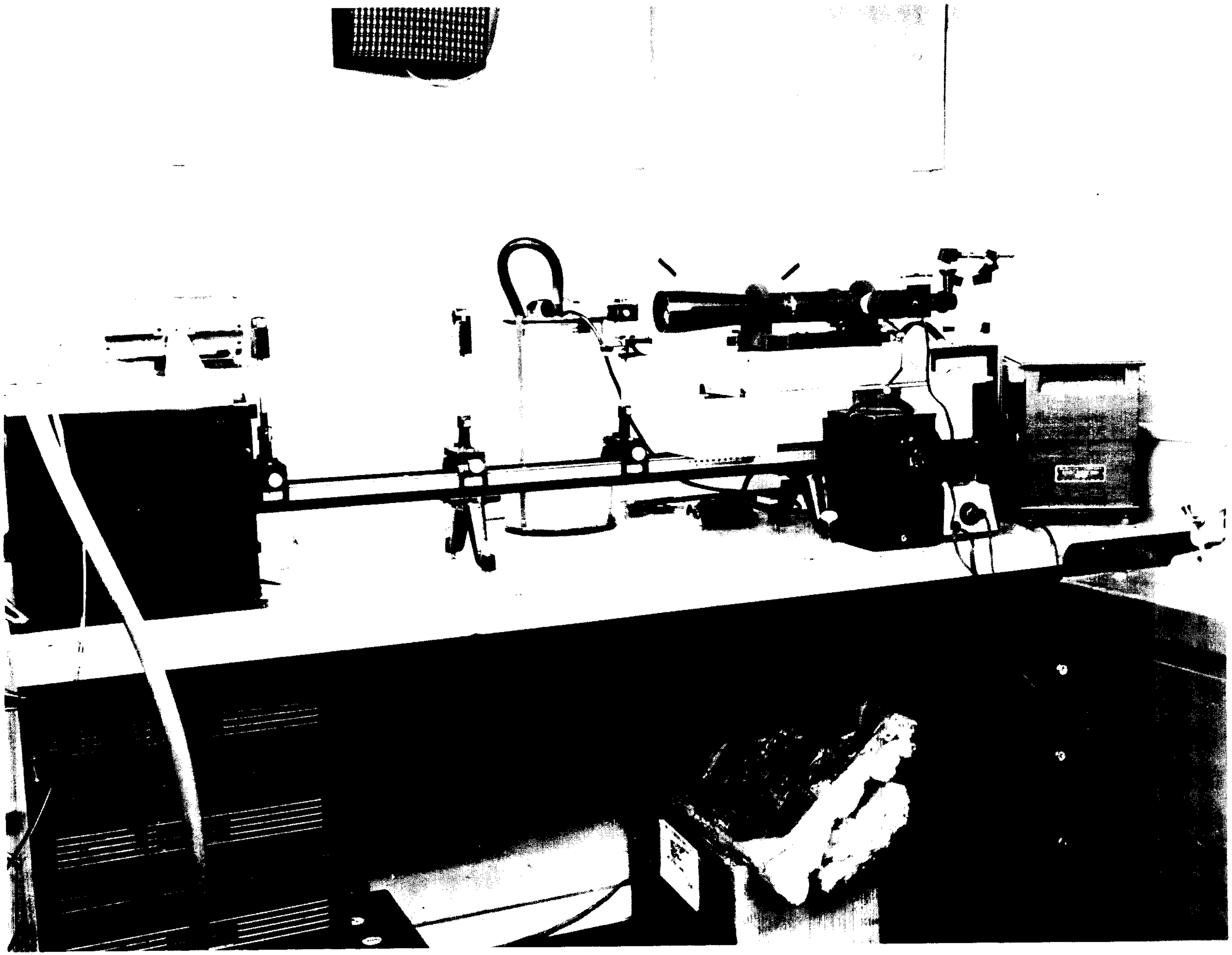


FIGURE 19. KERR CELL ALIGNMENT FOR LASER "Q" SPOILING EXPERIMENTS

advantages of high PRR's and long pulses are becoming more and more apparent [16]. For this reason, the 240 KJ system is being oriented toward lengthened pulses and high PRR's. A laser capable of 20 pulses per second at 10 Joules per pulse has already been reported. This is an output of about 200 watts. Further, it is contended that welding of materials up to 0.070 inch in thickness has been accomplished by focussing, flash lamp waveform and PRR optimization. It is stated that, "we found that welds approaching 10 pulses per second have a completely different characteristic than those in single shot, one-pulse-per-second system," and that "using these techniques we have been able to actually run a bead and raise the metal up from the surface, rather than crater the metal" [16].

Neuman's data indicates there is a good possibility that such relationships may apply. Platte and Smith also contend that if high repetition rates are attainable, it may be possible to weld thick plate with power densities presently available [17]. More recently, Anderson reported greatly improved aspect ratios and the possibility of welding thin sheet with outputs in the 10 to 100 watt range [18].

A simple approximation of what might be accomplished by a high PRR, long pulse approach using the 240 KJ system follows.

1. Possible arrangement: 10 pulses per second, 24 KJ input per pulse.

2. With output efficiency of .75 percent, 180 J per pulse, or 1800 J total energy in one second.

3. $\frac{1800 \text{ watt sec}}{\text{one sec}} = 1800$ watts output

4. Regarding electron beam energy required to weld 7075-T6 aluminum in 0.125 inch thickness, MSFC data indicates that 1.26 KJ per inch are required at 100 ipm to attain a certain specific weld configuration. In view of the recent findings, it is presumptious to draw a direct comparison between the electron beam requirement in the vacuum environment, but for a rough approximation, it will be of some value. Later, laser welding data may show error in this assumption.

5. The reflectivity of polished aluminum will increase the laser equivalent input energy requirement over that required by the electron beam, to a value of 2.1 KJ per inch.

6. So, in order to get 2.1 KJ per inch out of the laser, one could slow down the welding speed:

$$\text{Required} = \frac{2100 \text{ watt sec}}{\text{inch}}$$

$$\text{Available} = \frac{1800 \text{ watt sec}}{\text{sec}}$$

$$\text{Speed} = \frac{1800}{2100} \; \frac{\text{inch}}{\text{sec}} \times \frac{60 \text{ sec}}{\text{min}}$$

$$= 5.15 \text{ in/min}$$

7. Again, if we assume the efficiency to be lower at slower welding speed, an adjustment for energy lost must be made. Even so, it appears that if one can compare electron beam directly, and if high PRR's and long pulses are of limited value, even then, welding in 0.125 inch thickness aluminum should be feasible.

If, as several recent reports tend to indicate, high PRR's and long pulses do penetrate deeper with less lost energy, then much deeper penetrations could be anticipated. Continuous operation over long periods would require 30 to 50 gpm cooling water for a 30°C rise in temperature, but with such a large mass and radiating area involved, the thermal lag alone should allow much good PRR and pulse width data to be taken on weld samples. In terms of total energy output, the laser cannot match the electron beam yet. However, some very recent developments portend early progress in the area of continuous wave (CW) lasers, as well as in the high PRR technology.

SECTION V. FUTURE CW LASER ASPECTS

The advantages of a CW laser are immediately apparent. Even fairly high PRR's with fairly long pulses tend to have, in effect, some dead time in a given period of elapsed time. These rates are being increased as techniques develop, but the ultimate is CW. Until recently, CW lasers were considered to be relatively low powered devices with output in the milliwatts range. The He-Ne laser was fairly typical, and it required at least 50 watts of RF power to extract approximately 100 milliwatts output, at 6328 Å wavelength. This is approximately 0.2 percent efficient, and probably is not enough output to consider for any metallurgical applications. Recently, however, an argon laser has been operated CW at an output of ten watts [19]. The device had output in the blue-green portion of the spectrum with principal lines at 4880 Å and 5145 Å. The input power to the water-cooled discharge tube was approximately 10 KW. A higher wattage design is believed imminent, possibly to 100 watts when the reflector mirror problems are resolved. The important observation here is that the CW output power picture has changed by several orders of magnitude in only a very brief period of time and there seems little reason to doubt that this trend will continue.

The argon laser described operates on 50 amps d.c. and utilizes a 1000 gauss magnetic field to enhance the output. The engineering problem remaining to be solved is that of providing adequate cooling for the reflective mirrors. Figure 20 shows a crude sketch of the device.

Another recent announcement described a 6 watt CW output attained by a gallium arsenide semiconductor laser. Power efficiency was 40 to 50 percent, but the device must be operated at 4°K. While this device may not be too attractive for welding yet, this and the argon laser can be considered precursors of much more powerful devices. Progress is being made in this area, and it is only a question of engineering and time before lasers enter the higher power domain, presently dominated by electron beam systems. Even before this happens, however, better understanding of the effect of high PRR, pulse width, and other unknown factors should facilitate much wider application of current pulse sys-

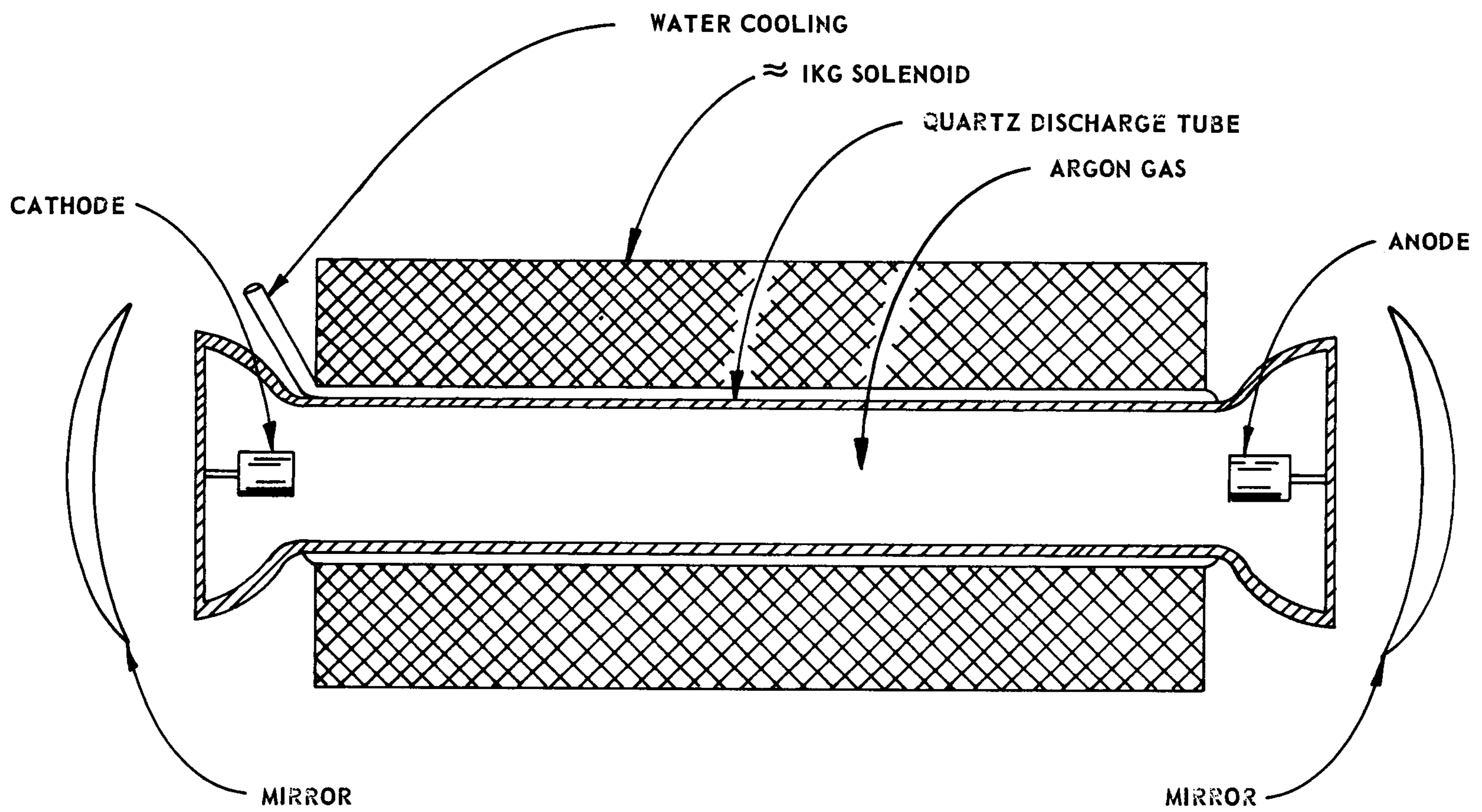


FIGURE 20. CONTINUOUS WAVE ARGON LASER

tems. The current status bears much resemblance to the "baby" in the famous anecdote concerning James Clerk Maxwell, the eminent Scottish physicist. When questioned bluntly regarding the value of one of his classic discoveries in electromagnetic theory, he calmly replied, "what good is a baby"? The analogy need hardly be drawn.

SECTION VI. CONCLUSIONS

Of the two basic laser materials, Nd-glass and pink ruby, the latter apparently offers more promise for very high power laser welding operations. Also, for very high powered systems, the co-axial gun with the helical flash tube configuration appears superior to either the close coupled or the elliptical geometry.

Focussing system problems are quite severe with energy levels above 200 kilojoules, and the Cassegranian approach seems an attractive means of maintaining a reasonable energy density level until the final focus spot position is reached.

So far, ruby quality control leaves much to be desired, as evidenced by fluctuations between apparently identical rubies. One of the best measuring devices used in determining laser output is the rat's nest calorimeter. Positive "focussed spot" energy density fluctuation measurements have not yet been made on the MSFC 240 kilojoule unit.

Stainless steel and aluminum foil have been successfully welded with a 4000 joule laser, and micro-welding is now also widely accepted, particularly by the electronics industry. Welding of aluminum, as with conventional techniques, required either an inert gas shield, or a vacuum environment. A laser beam can be projected from a shirtsleeve environment into a vacuum chamber, and acceptable welding actually accomplished.

Q-spoiling techniques, or giant pulses, are of little or no value in welding, and excessive power density results in vaporization and subsequent drilling instead of welding. Power densities exceeding 300,000 watts per square centimeter cause vaporization rather than welding.

Meteoroid simulation studies by NASA involving momentum transfer , and cratering effects produced by giant pulses, show that several component pulses occurring over a longer time interval cause more wave energy to be used for melting and less for evaporation. The advantages of higher pulse repetition rates, and longer pulses are becoming more and more apparent all the time. Further, there is some evidence that the weld bead aspect ratio and bead contour changes with increased PRR's and longer pulses.

Welding of 0.125 inch aluminum at a speed of 5.15 inches per minute seems within the current technology. The laser cannot yet match the electron beam in terms of total energy output.

Recent developments in the area of continuous wave lasers have demonstrated orders of magnitude improvement in output power, and 100 watts continuous seems imminent. Unquestionably, the laser welding field is in its infancy, and tremendous strides surely can be anticipated.

APPENDIX A

MATERIALS AND OUTPUT WAVELENGTHS OF VARIOUS TYPES OF LASERS

State and Material	Active Element	Wavelength (λ in Å or μ)	Excitation
1st CRYSTAL			
Pink ruby, Al_2OC	Cr^{3+} (R_2-R_1)	6929-6943 Å	Flashlamp, cont. lamp
Red ruby, Al_2O_3	Cr^{3+} (N_2-N_1)	7009, 7041 Å	Flashlamp, cont. lamp
Barium fluoride,	U^{3+}	2.556 μ	Flashlamp
BaF_2	Nd^{3+}	1.06 μ	Flashlamp
Calcium fluoride,			
CaF_2	Sm^{2+}	7083 Å	Flashlamp
	U^{3+}	2.24-2.61 μ	Flashlamp, cont. lamp
	Dy^{2+}	2.36 μ	Flashlamp, cont. lamp
	Tm^{2+}	1.116-1.189 μ	Flashlamp
	Ho^{3+}	2.05 μ	Flashlamp
	Nd^{3+}	1.046 μ	Flashlamp
Calcium molyb-			
date, $CaMo0_4$	Nd^{3+}	1.06 μ	Flashlamp, cont. lamp
Calcium tung-			
state $CaWO_4$	Nd^{3+}	1.063 μ	Flashlamp, cont. lamp
	Pr^{3+}	1.047 μ	Flashlamp
	Ho^{3+}	2.046 μ	Flashlamp
	Er^{3+}	1.612 μ	Flashlamp
	Tm^{3+}	1.911 μ	Flashlamp
Strontium tung-			
state, $SrWO_4$	Nd^{3+}	1.06 μ	Flashlamp, cont. lamp

APPENDIX A (Cont'd)

State and Material	Active Element	Wavelength (λ in Å or μ)	Excitation
Lanthanum trifluoride, LaF_3	Nd^{3+}	1.06 μ	Flashlamp, cont. lamp
	Pr^{3+}	5985 Å	Flashlamp
Strontium molyddate, $SrMoO_4$	Nd^{3+}	1.064 μ	Flashlamp
	Pr^{3+}	1.047 μ	Flashlamp
Strontium fluoride, SrF_2	U^{3+}	2.407 μ	Flashlamp, cont. lamp
	Sm^{2+}	6967 A	Flashlamp
	Tm^{3+}	1.91 μ	Flashlamp, cont. lamp
	Nd^{3+}	1.06 μ	Flashlamp, cont. lamp
$Na_{1/2}La_{1/2}MoO_4$	Nd^{3+}	1.06 μ	Flashtube, cont. lamp
Lead Molybdate $PbMoO_4$	Nd^{3+}	1.06 μ	Flashlamp, cont. lamp
2nd GAS			
Helium-Neon	Neon	0.6328 to > 3.39 μ	d.-c. and r-f discharge
Cesium		3.718 μ	Cont. lamp
Neon-Oxygen	Oxygen	8446 Å	d.-c. and r-f discharge
Argon-Oxygen	Oxygen	8446 Å	
Helium		2.0603 μ	
Neon		1.15-17.8 μ	

APPENDIX A (Cont'd)

State and Material	Active Element	Wavelength (λ in Å or μ)	Excitation
Argon		1.618-12.14 μ	
Krypton		1.69-7.06 μ	
Xenon		2.026, 5.574 μ 35 μ	
Helium-Xenon	Xenon	2.026-12.9 μ	
Nitrogen			Pulsed discharge
3rd SEMICONDUCTOR			
Gallium arsenide	p-n Junction	8400 Å	Pulsed or cont. d-c
Gallium arsenide phosphide		6500-8400 Å	Pulsed
Indium phosphide		9100 Å	Pulsed or cont. d-c
Indium arsenide		3.1 μ	Pulsed or cont. d-c
Indium antimonide		5.2 μ	Pulsed
4th LIQUID			
Benezene	Stimulated Raman scattering	8819, 7455 8052 Å	Ruby laser
Nitrobenzene	Stimulated Raman scattering	7568, 8539 9632 Å	Giant pulse ruby laser

APPENDIX A (Cont'd)

State and Material	Active Element	Wavelength (λ in Å or μ)	Excitation
Toluene	Stimulated Raman scattering	7463 Å	Giant pulse ruby laser
1 Bromonaphthalene	Stimulated Raman scattering	7672 Å	Giant pulse ruby laser
Pyridine	Stimulated Raman scattering	7457 Å, 8053 A	Giant pulse ruby laser
Cyclohexane	Stimulated Raman scattering	8658 Å	Giant pulse ruby laser
Dueterated benezene, C_6D_6	Stimulated Raman scattering	7430, 7990 Å	Giant pulse ruby laser
Europium benezolyacetonate in alcohol	Eu^{3+}	6100 Å	Flashlamp
5th PLASTIC			
Europium Triflurothienylbutaneodione in polymethyl methacrylate	Eu^{3+}	6130 Å	Flashlamp

APPENDIX A (Concluded)

State and Material	Active Element	Wavelength (λ in Å or μ)	Excitation
6th CLASS			
Borosilicate glass	Nd^{3+}	1.06 μ	Flashlamp, cont. lamp
Lanthanum-Borosilicate glass	Nd^{3+}	1.06 μ	Flashlamp
Li-Mg-Al-Si	Yb^{3+}	1.02 μ	Flashlamp
Li-Mg-Al-Si	Gd^{3+}	3125 Å	Flashlamp
Li-Mg-Al-Si	Ho^{3+}	1.95 μ	Flashlamp

APPENDIX B

PINK RUBY DATA

Ruby in Use at MSFC

1. Length - 12 inches
   Diameter - 0.625 inch
   Doping - Cr^{+++}0.04 percent
   Orientation - 90°
   Divergence Angle - $\approx$ 30" (of arc)

2. Rod has two facet roof at one end, and relies on reflected spontaneous decay radiation reflection back into ruby, due to dielectric discontinuity at exit end. All flats are accurate to 0.1 wavelength and optically parallel to within 2.5 seconds.

3. Operating wavelength at room temperature is 6943 Angstroms at (20°C). At -196°C, it is 6934 Angstroms. In the 20 to 90°C region, the wavelength can be calculated.

$$\lambda(\tau) + 6943.25 + .068 \ (T-20)$$

where T is in degrees centigrade.

General Data

1. Rods with zero degrees orientation exhibit circularly, or elliptically polarized output.

2. Rods with 90 degrees orientation (c-axis at right angle to rod axis) produce polarized beam.

3. The slope of the zero degree rod is much steeper than the 90 degree rod on the "temperature versus threshold" characteristic curve.

4. A sapphire overlay on the rod is reported to lower the threshold.

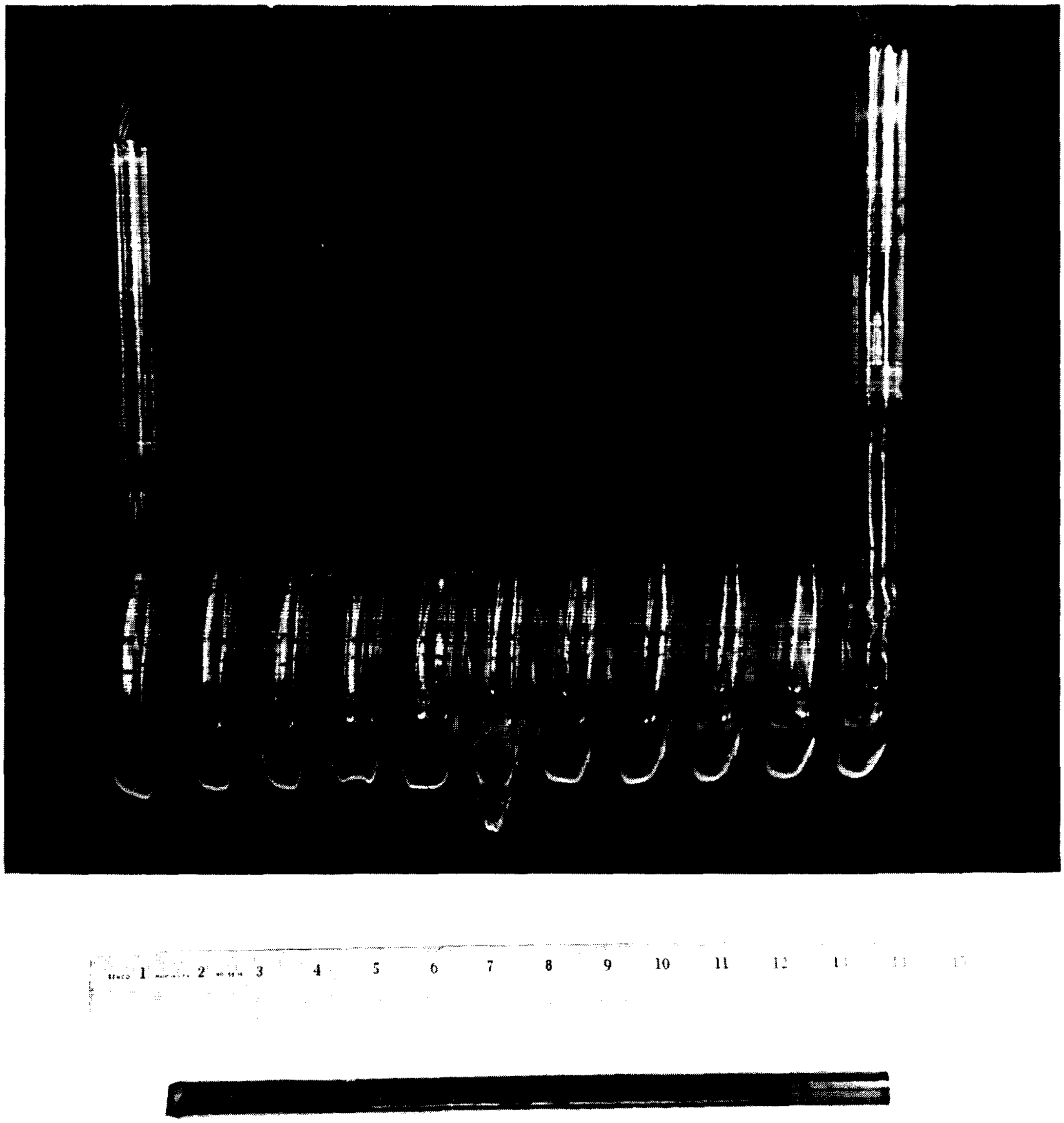
5. Rubies should not have polished walls, as this induces detrimental internal modes which are contained by total internal reflection and tend to give nonbeneficial de-excitation of the ions [7]. In addition, polished walls tend to focus the light in the center of the rod, thereby giving a lower threshold, but less efficiency results above threshold where welding lasers operate. Fine-ground rods are preferred.

6. As the Cr^{+++} ion concentration is lowered, the gain per passage through the ruby decreases, thus increasing the threshold. If the Cr^{+++} ion concentration increases or the diameter of the rod increases, or both increase, the rod becomes "optically thick"

to pumping radiation and gets more difficult to pump. When the length of the rod is increased, gain increases and the threshold is lowered. Decreasing the operating temperature of the rod results in increased gain and lowered threshold.

7. Maximum pump energy density does not appear at the surface of the rod - it will occur somewhere inside the rod [8].

8. A typical large ruby can be seen below.



240 KJ LASER RUBY AND FLASH TUBE

APPENDIX C

COAXIAL FLASHTUBE DATA

Helix Length - 13 1/4 inches overall (12 inches CL to CL of legs)

Diameter - 5 inches

Tubing Material - Quartz

Tubing Diameter - 25 m/m, 25 m/m ergs

Rated Energy - 240, 000 Joules

Series Inductance - 300 μh

Electrodes - 7/8 inch

Tube Threshold - 8 KV, with 50 to 80 KV trigger pulse

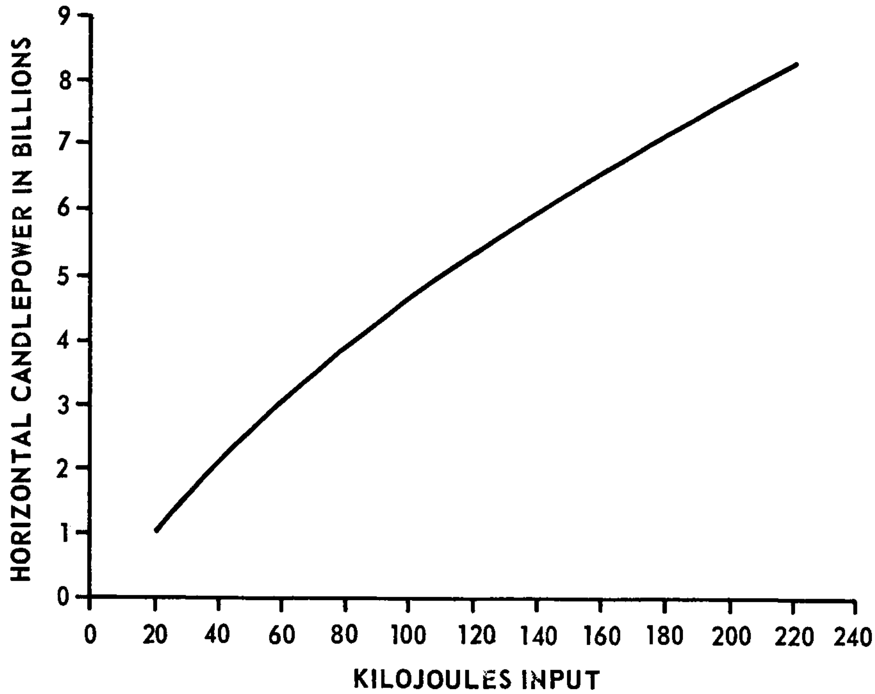
Maximum Impressed Voltage - 20 KV

Manufacturer - Kemlite Laboratories, Inc. Chicago 22, Illinois

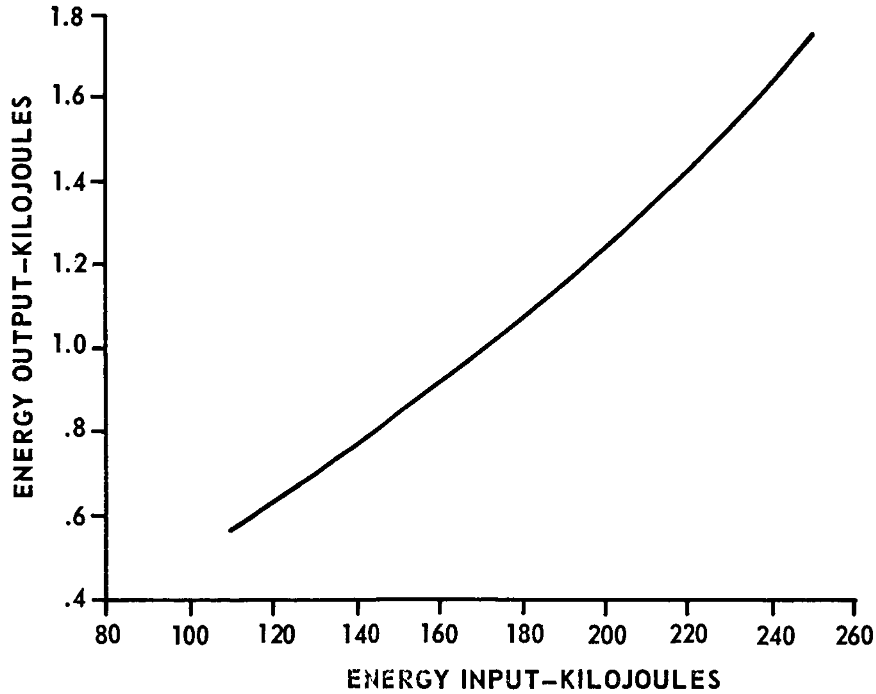
Notes

1. Quartz emits energy in ultra-violet spectral region - some filtering desirable to prevent ruby "bleaching."

2. Cleanliness absolutely essential - clean with alcohol i.e., fingerprints, etc., "burned in" during flashing.



XE FLASH TUBE 25HH300-44U LIGHT OUTPUT
IN HCP X 10^9 VS. ENERGY INPUT IN KJ



OUTPUT VS. INPUT - 240KJ LASER

OUTPUT POWER MEASUREMENT
0.625 INCH RUBY LASER

1. RUBY TEMPERATURE, 200 F
2. CAPACITANCE 1200 MFD.
3. CALORIMETER CALIBRATION 1.6MV=1 JOULE
4. BEAM SPLITTER ATTENUATION 1000
5. TRANSMISSON OF CALORIMETER WINDOW 91%

BANK VOLTS KV	ENERGY IN K JOULES	LASER OUTPUT JOULES	LAMP CURRENT AMP.	CALORIMETER M VOLTS
12	86.4	–	4000	–
14	117.6	634	4500	0.36
16	153.8	880	6000	0.50
18	194.1	1,108	7125	0.63
20	240.0	1,670	8250	0.95

REFERENCES

1. Snitzer, E., "Neodymium Glass Laser," American Optical Company, Southbridge, Massachusetts, U.S. Army Research Office (Durham) Contract DA-19-020-ORD-5575.

2. Snitzer, E., Phys. Rev. Letters 7, 510, 1961.

3. Snitzer, E., "Neodymium Glass Laser," Proceedings of the Third International Congress of Quantum Electronics, Columbia University Press, New York, 1964.

4. Schawlow, A. L., "Infrared and Optical Masers," The Solid State Journal, June 1961, p. 27.

5. Cummins, H. Z., I. D. Abella, "Thermal Tuning of Ruby Optical Maser," Journal Applied Physics, 32, 1177, 1961.

6. Piper, N. B., Electronics, Oct. 27, 1961.

7. Dobratz, B. E., R. S. Congleton, and W. R. Sooy, "Dynamic Limitations on the Attainable Inversion in Ruby Lasers," Proceedings of the Third International Congress, Quantum Electronics, Columbia University Press, New York, 1964.

8. D'Haenens, I. J., and V. Evtauhov, "Temperature and Concentration Effects in a Ruby Laser," Quantum Electronics, Columbia University Press, New York, 1964.

9. Maiman, T. H., Phys. Rev. Letters, Vol. 4, p. 504, June 1960.

10. Collins, R. J., et al., Phys. Rev. Letters, Vol. 5, p. 303, Oct. 1960.

11. Li, T., and S. D. Sims, "Observations on the Pump-Light Intensity Distribution of a Ruby Optical Maser with Different Pumping Schemes," Proc. IRE, Vol. 50, April 1962.

12. Reich, S., "Laser (Optical Maser) Beam Fusion Welding," Interim Engineering Prog. Report No. IR-7-985 (VII), ASD Proj. No. 7-985, U.S.A.F., Feb. - May 1964.

13. Congleton, R. S., W. R. Sooy, D. R. Dewhirst, and L. D. Riley, "Comparison of Excitation Geometries for Ruby Lasers," Quantum Electronics," Columbia University Press, N.Y. 1964.

14. Cooper, C. R., J. R. Rasquin, "High Energy Xenon Flashtube for Optical Pumping," Manufacturing Development Memorandum MDM-R-ME-ME 8-64, Marshall Space Flight Center, April 1964.

REFERENCES (Concluded)

15. Neuman, Frank, "Momentum Transfer and Cratering Effects Produced by Giant Laser Pulses," Applied Physics Letters, May, 1964.

16. Hardway, Glenn, A., "On Long Pulse Welding," Electronics, Reader Correspondence, Nov. 1964.

17. Platte, W. N.,, and J. F. Smith, "Laser Techniques for Metals Joining," Supplement to the Welding Journal, Nov. 1963.

18. Anderson, J. E., "Laser Welding," University Research Conference, Detroit, Mich. May 6, 1964.

19. Statz, Hermann, Asst. Mfg. Rsch. Div., Raytheon Company, Personal Communication, January 1965.

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LASER WELDING

By

R. J. Schwinghamer

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R. J. Schwinghamer

R. J. SCHWINGHAMER
Deputy Chief, Manufacturing
Research and Technology Division

J. P. Orr

J. P. ORR
Chief, Manufacturing Research
and Technology Division

W. Kuers

WERNER R. KUERS
Director, Manufacturing Engineering
Laboratory

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